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Cholesterol Lowering in Low Density Lipoprotein Receptor Knockout Mice Overexpressing Apolipoprotein E

Jun-ichi Osuga,* Mari Yonemoto,† Nobuhiro Yamada,* Hitoshi Shimano,* Hiroaki Yagyu,* Ken Ohashi,* Kenji Harada,* Toshio Kamei,† Yoshio Yazaki,* and Shun Ishibashi*

*The Third Department of Internal Medicine, Faculty of Medicine, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8655, Japan; and †Tsukuba Research Institute, Banyu Pharmaceutical Co., Ltd., 3 Okubo, Tsukuba, Ibaragi 300-33, Japan

Abstract

Apo E is a key molecule in the lipoprotein metabolism; thus, genetic manipulation of apo E may prove useful in the treatment of hypercholesterolemia. To test the feasibility of this idea, we have generated low density lipoprotein receptor (LDLR) knockout mice that overexpress the rat apo E transgene (ETg+/−:LDLRKO), and compared their plasma lipoprotein profiles with those of nonexpressing LDLR knockout mice (ETg−−:LDLRKO). On a normal chow diet, the mean plasma cholesterol level of ETg+/−:LDLRKO mice was significantly lower than that of ETg−−:LDLRKO mice (189 versus 240 mg/dl, P < 0.01). The LDL fraction was selectively reduced in the ETg+/−:LDLRKO mice. Despite the challenge with an atherogenic diet, cholesterol lowering was persistently observed and fatty streak lesions in the aortic sinus were significantly suppressed in the mice overexpressing apo E. These results imply that stimulation of hepatic production of apo E may be used as a promising adjunctive therapy for homozygous familial hypercholesterolemia. (J. Clin. Invest. 1998. 102:386–394.) Key words: apo E • low density lipoprotein receptor • hypercholesterolemia • knockout mouse • atherosclerosis

Introduction

Apo E plays a crucial role in the metabolism of plasma lipoproteins (1). Apo E is produced primarily by the liver and distributed in all classes of lipoproteins. In particular, the plasma metabolism of triglyceride (TG)-rich lipoproteins such as chylomicron, VLDL, and intermediate density lipoprotein (IDL) is profoundly influenced by apo E. Several distinct mechanisms have been proposed to explain the role of apo E in the metabolism of TG-rich lipoproteins. First, apo E binds to the low density lipoprotein receptor (LDLR) with a high affinity, thereby facilitating the LDLR-mediated hepatic lipoprotein uptake (2, 3). Second, apo E binds to cell surface proteoglycans, thereby sequestering the apo E-containing lipoproteins to the surface of cells such as hepatocytes and vascular endothelial cells in the space of Disse of the liver (4). Third, evidence suggests that other endocytic lipoprotein receptors are involved in the hepatic uptake of chylomicron remnants (CR), lipoproteins extremely rich in apo E (5, 6). Herz and his colleagues have shown that LDLR-related protein, a multifunctional behemoth receptor belonging to the LDLR gene family, is responsible for the hepatic uptake of CR in the absence of the LDLR (7–9).

The cholesterol lowering may result from augmented hepatic uptake of the lipoproteins, because 125I-labeled VLDL or LDL were cleared from the plasma faster in these ETg mice (14). In addition, the plasma excursions of retinyl ester, an indicator of chylomicron and CR, were markedly suppressed in the ETg mice, after intragastric bolus administration of retinol (14). Based on these results, we proposed that the overexpressed apo E enhances the plasma clearance of lipoproteins of both hepatic and intestinal origin. However, whether or not the pathway by which this clearance is mediated involves the LDLR remains unknown.

The present study was undertaken to test the feasibility of the idea that genetic manipulation of apo E is useful for the treatment of hypercholesterolemia arising from the LDLR deficiency. We have cross-bred the ETg mice to LDLR knockout (LDLRKO) mice, generated LDLRKO mice possessing the apo E transgene in a heterozygous (ETg+/−:LDLRKO) or homozygous form (ETg−−:LDLRKO), and compared their plasma lipoprotein metabolism and atherosclerosis with those of nonexpressing LDLRKO (ETg−−:LDLRKO) mice.
Methods

Mice. Generation of E\textsubscript{Tg} (13) and LDLRKO mice (15) were described in the indicated references. PCR was performed to determine the wild-type and mutated LDLR allele using the following sets of primers: primer A (5\textsuperscript{'}-GATTCAGGAGATGGCAA-3\textsuperscript{'}) and primer B (5\textsuperscript{'}-CGCAATGTGCTTCATCAG-3\textsuperscript{'}), yielding a 354-bp fragment for the wild-type allele and a 1.7-kb fragment for the disrupted allele; and primer C (5\textsuperscript{'}-GATTGGAAGACAATAGCAG-GCATGC-3\textsuperscript{'}) and primer D (5\textsuperscript{'}-GGCAAGATGGCTCAGCAAGGAAGGC-3\textsuperscript{'}), yielding a 1.49-kb fragment for the disrupted allele. Southern blot analyses for the apo E transgene were described previously (13). The radioactivities were measured by BAS2000 (Fuji Film, Tokyo, Japan) to discriminate between the heterozygotes and homozygotes. Male LDLRKO mice were mated to female E\textsubscript{Tg} mice. The resulting offspring, which were heterozygous for the apo E transgene and were obligatorily heterozygous for the disrupted LDLR locus (E\textsubscript{Tg}-/-:LDLR\textsuperscript{-/-}), were further bred to LDLRKO mice to produce LDLRKO mice heterozygous for the apo E transgene (E\textsubscript{Tg}-/-:LDLR\textsuperscript{-/-}:LDLR\textsuperscript{KO}). Brother-sister mating of the E\textsubscript{Tg}-/-:LDLR\textsuperscript{-/-} mice was performed to generate E\textsubscript{Tg}-/-:LDLR\textsuperscript{-/-} and E\textsubscript{Tg}-/-:LDLR\textsuperscript{KO} mice with comparable genetic background: 50% from C57BL/6J, 37.5% from 129Sv, and 12.5% from DBA/2.

Mice were maintained on a 12-h dark/light cycle and were allowed access to food and water ad libitum. Two diets were used: (a) a normal chow diet (Lab Diet 5002, PMI Feeds, Inc., St. Louis, MO) that contained 4.5% animal fat and 0.025% cholesterol, 1.16 mM Zn, 1.36 mM Mn, 0.27 mM Cu, 0.01 mM Fe, and 0.04 mM Cr; (b) a 1.25% cholesterol/atherogenic diet (three parts of the normal diet mixed with one part of a cholesterol, cocoa butter, casein, and sodium cholate diet [Thomas Hartroft diet; PMI Foods Inc.]). The final diet contained 1.25% cholesterol, 7.5% cocoa butter, 7.5% casein, and 0.5% sodium cholate. For induction of the metalloproteinase promoter, water supplemented with 20 mM ZnSO\textsubscript{4} was administered for 2 wk (13). Experiments were performed in accordance with institutional guidelines. Unless otherwise stated, mice aged between 12–16 wk were used for the experiments.

Plasma lipid analysis. Blood was collected from the retroorbital plexus into a tube containing EDTA after a 12-h fast, and plasma was separated by centrifugation and mixed with 1/500 vol of a solution containing 60 mg/ml of benzamidine. TC and TG concentrations were determined enzymatically using kits (Determiner TC555 and Determiner TG555; Kyowa Medex, Tokyo, Japan). For lipoprotein analyses, the plasma was immediately applied to high performance liquid chromatography (HPLC) or sequential ultracentrifugation. HPLC analyses were performed according to a modified method of Harjani and Okazaki (16). 5 \mu l of plasma was applied to a combined column system composed of two TSK gel Lipopropacks (TOSOH; Tokyo, Japan) in tandem, and eluted with the supplied buffer (TSK eluent LP1; TOSOH) at a rate of 0.5 ml/min. TC concentrations in the effluents were monitored using a kit (Determiner TC555). Areas under the elution curves for HDL and non-HDL peaks were determined. These values and plasma TC levels were used to calculate non–HDL- and HDL-cholesterol concentrations.

Quantitation of apo B. Plasma apo B concentrations were determined by isopropanol precipitation method as described (17). In brief, 100 \mu l of plasma was obtained from an individual mouse and ultracentrifuged at a density of 1.063 g/ml. An aliquot of the top d < 1.063 g/ml lipoprotein fraction was mixed with an equal volume of isopropanol in a microfuge tube, incubated at room temperature for 1 h, and centrifuged at 10,000 \times g for 15 min. The resulting protein pellets were resuspended in 0.1 N NaOH, and protein concentrations were determined by a kit (BCA protein assay reagent; Pierce, Rockford, IL). In parallel, apo B concentrations were determined by a single radial immunodiffusion (SRID) technique using a kit designed for measurement of human apo B levels (Apo B plate ‘Daiichi’; Daiichi Pure Chemicals, Tokyo, Japan), according to a manufacturer’s instruction (18). When the same amounts of LDL apo B were applied to the plates, mouse LDL apo B produced a 3.7-fold larger precipitation ring in diameter than human LDL apo B. The results of the isopropanol precipitation method were correlated with those of the SRID method with r > 0.99; n = 9.

Quantitation of apo E. Immunoblot analyses were performed to determine plasma apo E levels. 1 \mu l of plasma was subjected to both SDS-PAGE; Y, proportion of the radioactivities in rat apo E (three bands together) in all the apo E radioactivities (rat plus mouse) on IEF; A, radioactivity of the standard rat apo E; and B, the antibody’s immunoreactivity for rat apo E compared to that for mouse apo E. Rat and mouse apo E concentrations were calculated from the following formulas: Rat apo E concentration = X \times Y/A; Mouse apo E concentration = B \times X \times (1 – Y)/A.

Analyses of plasma lipoprotein and apolipoproteins. Preparative ultracentrifugation was performed to obtain CM + VLDL (d < 1.006 g/ml), LDL (d 1.006–1.019 g/ml), HDL (d 1.019–1.063 g/ml) and HDL (1.063–1.21 g/ml) from the pooled plasma as described (20). TC contents were measured and represented as mg/dl of original plasma. After dialysis against saline containing 0.2 mM EDTA and 1 mM PMSF, each lipoprotein fraction was delipidated overnight at −20°C with 20 vol of ice-cold ethanol-diethyl ether (3:1, vol/vol), and the apolipoproteins were pelleted by centrifugation for 20 min at −10°C, 1,000 g (21). The pellets were extracted twice with cold anhydrous diethyl ether, and subjected to SDS/3–15% PAGE. Proteins were visualized by staining with Comassie brilliant blue. The intensities of the bands were determined by densitometric scanning and quantified by National Institutes of Health Image software (Bethesda, MD).

Plasma lipoprotein kinetics. After a 12-h fast, blood was obtained from E\textsubscript{Tg}-/-:LDLR\textsuperscript{KO} or E\textsubscript{Tg}-/-:LDLR\textsuperscript{KO} mice (n = 10) that had been maintained on water supplemented with zinc and a normal chow, and pooled for lipoprotein isolation. VLDL (d < 1.006 g/ml) and LDL (d 1.019–1.063 g/ml) were isolated by ultracentrifugation and refloated at the same density to increase the purity. VLDL obtained from E\textsubscript{Tg}-/-:LDLR\textsuperscript{KO} or E\textsubscript{Tg}-/-:LDLR\textsuperscript{KO} mice are denoted as E–VLDL or E+VLDL, respectively. These lipoproteins and the infranatant d > 1.063 g/ml fraction were dialyzed against saline containing 1 mM sodium phosphate, pH 7.4, 0.2 mM EDTA, and 1 mM PMSF. The lipoproteins were labeled with \textsuperscript{125}I by iodine monochloride method (22), and dialyzed as described above. After removing EDTA and PMSF by dialysis against PBS, the labeled lipoproteins were mixed with the d > 1.063 g/ml fraction, and diluted with PBS containing 10 mg/ml BSA to 40 \mu g/ml. 100 \mu l (equivalent to 4 \mu g protein of the lipoprotein) was injected as a bolus into the jugular vein of mice that had been maintained on water containing zinc for 2 wk, under anesthesia with pentobarbital. Subsequently, blood was collected from the retroorbital plexus at the indicated times. Apo B–associated radioactivities were determined by the isopropanol precipitation method as described (14). The value at 1 min after injection was used as 100%. Fractional catabolic rate (FCR) and production rate were calculated according to Matthews (23).

Vitamin A fat tolerance test. After a 4-h fast, 100 \mu l of Cholata \textsuperscript{A} (Eisai Co., Ltd.; Tokyo, Japan) containing 2 mg of retinyl palmitate and 10.6 mg castor oil was administered as a bolus through a gastric cannula to mice that had been maintained on water supple-
mented with zinc, without anesthesia. Blood was collected from the retroorbital plexus at the indicated times. Plasma was immediately separated and stored wrapped in foil at −20°C. After extraction with hexane from pooled plasma, the lipids were subjected to HPLC for the measurement of retinyl palmitate and retinol, as previously described (14).

Pathology. The hearts and attached aortas were removed, fixed with saline containing 4% formalin, embedded in 25% gelatin, and sectioned as described (24). Briefly, 10 μm cross-sections were taken sequentially, starting just above the aortic valve and moving along the ascending aorta. Five sections, each separated by 120 μm, were used to evaluate the lesions. Fatty streak lesions were stained using Oil Red O. The lesion area of each section was estimated by a digitizing tablet (NEC PC-8875 personal TABLET).

Statistics. Student’s t test was used to compare the values between two groups.

Results

Expression of rat apo E. Immunoblot analyses were performed to measure the plasma concentration of apo E (Fig. 1). Fig. 1 A compares the intensities of bands corresponding to apo E purified from mice and rats, when the same amounts (75 ng) were loaded to the gels; the antibody had twofold higher immunoreactivity for rat apo E than for mouse apo E. Fig. 1 B shows immunoblot of SDS-PAGE (top) and IEF (bottom) for the plasma apo E of the three types of mice before and after zinc treatment. SDS-PAGE revealed that plasma apo E levels were higher in the mice having the rat apo E transgene than those without it in the following order before zinc treatment: ETg+/−:LDLRKO > ETg+/+:LDLRKO > ETg−/−:LDLRKO. After zinc treatment, plasma apo E levels were further increased in the ETg−/−:LDLRKO mice. Upon IEF, mouse apo E was focused as a single band, and rat apo E was focused as three bands that were more acidic than mouse apo E. Presumably, the most basic band of rat apo E is nonsialidated apo E and the second and third bands are with one and two molecules of sialic acid, respectively. Furthermore, the IEF results confirm that rat apo E was present only in the ETg+/−:LDLRKO and ETg+/+:LDLRKO mice, but not in the ETg−/−:LDLRKO.

Table I summarizes the calculated values for the plasma levels of rat and mouse apo E. Before zinc treatment, the ETg+/−:LDLRKO and ETg+/+:LDLRKO mice had rat apo E in the plasma in amounts comparable to 50% of mouse endogenous apo E. The ETg+/−:LDLRKO mice had 40% higher concentrations of rat apo E than the ETg+/+:LDLRKO mice. After zinc treatment, the rat apo E levels were increased by 38% in the ETg+/−:LDLRKO mice and by 23% in the ETg+/+:LDLRKO mice.

![Figure 1](image_url)

**Figure 1.** Immunoblot analyses of plasma apo E in ETg+/−:LDLRKO (−/−), ETg+/+:LDLRKO (+/−), and ETg+/+:LDLRKO mice (+/+), maintained on a normal chow. (A) Difference of the immunoreactivity of the antibody. The same amount of rat and mouse apo E (75 ng) was subjected to SDS-PAGE. (B) Immunoblot of apo E separated by SDS-PAGE and IEF. Blood was collected from four mice with the indicated genotypes after a 12-h fast, before and after treatment with zinc. 1 μl of pooled plasma was subjected to SDS-PAGE and IEF analyses. (C) Immunoblots of apo E in VLDL, IDL, LDL, and HDL. Lipoproteins were separated from pooled plasma (n = 10) after treatment with zinc by sequential ultracentrifugation. Each lipoprotein fraction equivalent to 2 μl of original plasma was subjected to SDS-PAGE.
the plasma TC levels decreased by 20% in the significantly between these mice. After zinc treatment for 2 wk, the three types of mice, before and after zinc treatment (Table I). The plasma apo E levels were determined by immunoblot analyses as described in Methods. The values are expressed as means±SD. *P < 0.05 versus before of −/−; †P < 0.01 versus after of −/−; ‡P < 0.05 versus after of +/+ and −/−; §P < 0.05 versus before.

Table I. Plasma Apo E Levels

<table>
<thead>
<tr>
<th>Tg</th>
<th>n</th>
<th>Zn</th>
<th>Total apoE</th>
<th>Mouse apoE</th>
<th>Rat apoE</th>
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<tr>
<td>−/−</td>
<td>4</td>
<td>Bf</td>
<td>19.7±3.7</td>
<td>19.7±3.7</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Af</td>
<td>18.4±1.8</td>
<td>18.4±1.8</td>
<td>0</td>
</tr>
<tr>
<td>+/+</td>
<td>4</td>
<td>Bf</td>
<td>22.8±2.7</td>
<td>15.5±0.7</td>
<td>7.2±2.9</td>
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<tr>
<td></td>
<td></td>
<td>Af</td>
<td>26.5±1.2†</td>
<td>16.6±1.4†</td>
<td>9.9±2.5‡</td>
</tr>
<tr>
<td>+/+</td>
<td>4</td>
<td>Bf</td>
<td>27.4±3.5*</td>
<td>17.1±1.9</td>
<td>10.3±2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Af</td>
<td>26.2±2.3†</td>
<td>13.6±1.1†</td>
<td>12.7±3.2</td>
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</table>

LDLRKO mice. But the mouse apo E levels were decreased in the ETg+/−:LDLRKO mice; therefore, the combined apo E concentrations were not changed.

Fig. 1 C illustrates the combined apo E levels in each lipoprotein fraction from the three types of mice treated with zinc. In any lipoprotein classes, the LDLRKO mice with rat apo E transgene had more apo E than the LDLRKO mice without the transgene. The apo E contents were highest in LDL fraction irrespective of the presence of the transgene. Mild gene-dosage effects were seen in VLDL and IDL fraction.

Plasma lipoprotein profiles. To determine whether constitutive expression of the apo E transgene alters plasma lipid levels, the plasma TC and TG levels were compared between the three types of mice, before and after zinc treatment (Table II). Before zinc treatment, neither plasma TC nor TG differed significantly between these mice. After zinc treatment for 2 wk, the plasma TC levels decreased by 20% in the ETg+/−:LDLRKO mice and by 25% in the ETg+/−:LDLRKO mice, but not in the ETg−/−:LDLRKO mice. Such cholesterol lowering was largely attributable to the reduction in the non–HDL-C as shown in Fig. 2; the non–HDL-C was reduced by 20% in the ETg+/−:LDLRKO mice, and by 32% in the ETg+/−:LDLRKO mice (Table II).

To further determine which lipoprotein fraction was affected by the expression of rat apo E, we measured the TC and apo B contents in the lipoproteins isolated from the three types of mice treated with zinc (Table III). The most outstanding changes were observed in the TC and apo B-100 contents in the LDL fraction. TC contents in the LDL were reduced by 25% in the ETg+/−:LDLRKO mice and by 39% in the ETg+/−:LDLRKO mice; apo B-100 contents in the LDL were reduced by 23% in the ETg+/−:LDLRKO mice, and by 43% in the ETg+/−:LDLRKO mice. Thus, the changes in the LDL–TC appeared comparable to those in the LDL–apo B-100, indicating

Table II. Plasma Lipid Levels

<table>
<thead>
<tr>
<th>Tg</th>
<th>n</th>
<th>Zn</th>
<th>TC</th>
<th>Non–HDL-C</th>
<th>HDL-C</th>
<th>TG</th>
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<tr>
<td>−/−</td>
<td>15</td>
<td>Bf</td>
<td>260±68.6</td>
<td>137±52.6</td>
<td>121±28.1</td>
<td>127±55.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Af</td>
<td>240±60.8*</td>
<td>122±44.1</td>
<td>117±28.3</td>
<td>104±39.0</td>
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<tr>
<td>+/+</td>
<td>29</td>
<td>Bf</td>
<td>254±54.9</td>
<td>132±38.1</td>
<td>122±28.6</td>
<td>124±36.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Af</td>
<td>203±50.0*</td>
<td>105±32.5‡</td>
<td>108±27.9‡</td>
<td>128±40.2</td>
</tr>
<tr>
<td>+/+</td>
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<td>Bf</td>
<td>251±46.5</td>
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<td>189±31.2†</td>
<td>87±17.4‡</td>
<td>101±31.1</td>
<td>132±43.8</td>
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</table>

Figure 2. HPLC profiles of plasma lipoproteins from mice maintained on a normal chow. Plasma was obtained from five male ETg+/−:LDLRKO (A, −/−), ETg+/−:LDLRKO (B, +/+), and ETg+/−:LDLRKO mice (C, +/-) maintained on a normal chow and water supplemented with zinc. Pooled plasma from each group was subjected to HPLC lipoprotein analysis, and cholesterol contents in effluents were monitored.

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Table III. Cholesterol, Apo B-100, and Apo B-48 Composition in the Plasma Lipoproteins

<table>
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<tr>
<th></th>
<th>Tg</th>
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<th>IDL</th>
<th>LDL</th>
<th>HDL</th>
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<tr>
<td></td>
<td>mg/dl</td>
<td></td>
<td></td>
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<tr>
<td>Cholesterol</td>
<td></td>
<td>26</td>
<td>20</td>
<td>115</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>+/-</td>
<td>35</td>
<td>12</td>
<td>86</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>++/</td>
<td>25</td>
<td>11</td>
<td>70</td>
<td>80</td>
</tr>
<tr>
<td>Apo B-100/Apo B-48</td>
<td>-/-</td>
<td>0.8/1.0</td>
<td>0.2/0.5</td>
<td>89.5/7.0</td>
<td>N.D.</td>
</tr>
<tr>
<td></td>
<td>+/-</td>
<td>0.8/1.2</td>
<td>0.2/0.7</td>
<td>69.2/5.3</td>
<td>N.D.</td>
</tr>
<tr>
<td></td>
<td>++/</td>
<td>1.3/1.4</td>
<td>0.3/0.7</td>
<td>50.6/3.8</td>
<td>N.D.</td>
</tr>
</tbody>
</table>

The overexpression of rat apo E reduced the particle number of the apo B-100-containing lipoproteins primarily in the LDL fraction.

SDS/PAGE of apolipoproteins shows that apo B-100, a predominant apo B species, in the LDL fraction was reduced in the \( \text{ETg}^{+/+}:\text{LDLRKO} \) and \( \text{ETg}^{+/+}:\text{LDLRKO} \) mice, compared to the \( \text{ETg}^{-/-}:\text{LDLRKO} \) mice (Fig. 3). VLDL and IDL contained less apo B-100 than LDL, and there was no significant difference in its contents between the three types of mice. Consistent with the immunoblot results (Fig. 1), the \( \text{ETg}^{-/-}:\text{LDLRKO} \) and \( \text{ETg}^{+/+}:\text{LDLRKO} \) mice contained more apo E than the \( \text{ETg}^{-/-}:\text{LDLRKO} \) mice, especially in the VLDL fraction. No significant difference was observed in the composition of the other apolipoproteins such as apo A-I and apo B-48 between the three types of mice.

Lipoprotein kinetics studies. To clarify how the overexpression of rat apo E reduced plasma cholesterol levels even in the absence of the LDLR, lipoprotein kinetics studies were performed (Fig. 4). When injected into wild-type mice with the functional LDLR, \( ^{125}\text{I}-\text{E} \) was cleared faster than \( ^{125}\text{I}-\text{E} \); their \( t_{1/2} \) were 15 and 25 min, respectively (Fig. 4A). The mean FCR of \( ^{125}\text{I}-\text{VLDL} \) were 1.6 times larger than that of \( ^{125}\text{I}-\text{E} \) (2.17 versus 1.33 pools/h; \( P < 0.05 \)).

Next, \( ^{125}\text{I}-\text{E} \) were injected into the \( \text{ETg}^{+/+}:\text{LDLRKO} \) and \( ^{125}\text{I}-\text{VLDL} \) were injected into the functional LDLR, \( ^{125}\text{I}-\text{E} \) was cleared faster than \( ^{125}\text{I}-\text{E} \); their \( t_{1/2} \) were 90 min. After 6 h, however, \( ^{125}\text{I}-\text{E} \) and \( ^{125}\text{I}-\text{VLDL} \) were cleared faster than \( ^{125}\text{I}-\text{E} \) and \( ^{125}\text{I}-\text{VLDL} \). Overall, the mean FCR of \( ^{125}\text{I}-\text{E} \) was 1.45 times larger than that of \( ^{125}\text{I}-\text{E} \) (0.33 versus 0.23 pools/h, \( P < 0.05 \)). The mean production rate of apo B was calculated to be 21.2 and 18.4 nmol/h/g body weight for the \( \text{ETg}^{-/-}:\text{LDLRKO} \) and \( \text{ETg}^{+/+}:\text{LDLRKO} \) mice, respectively (Fig. 4B).

A similar kinetic study was performed using autologous LDL. There was no difference in the plasma clearance of LDL between the \( \text{ETg}^{-/-}:\text{LDLRKO} \) and \( \text{ETg}^{+/+}:\text{LDLRKO} \) mice up to 24 h (data not shown).

A vitamin A fat tolerance test did not reveal any difference in the plasma excursion of retinyl ester between the three
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Resistance against diet-induced hypercholesterolemia. The response of plasma TC and TG levels to the feeding with a 1.25% cholesterol/atherogenic diet was shown in Table IV. During the feeding, the mice had been maintained on water supplemented with zinc. The \( \text{ETg}^{+/-}:\text{LDLRKO} \) mice developed severe hypercholesterolemia with a mean plasma TC level of 3,116 mg/dl, which is similar to the previously reported values (16). The \( \text{ETg}^{+/-}:\text{LDLRKO} \) and \( \text{ETg}^{+/-}:\text{LDLRKO} \) mice exhibited milder hypercholesterolemia compared with the \( \text{ETg}^{+/-}:\text{LDLRKO} \) mice, indicating that the overexpression of rat apo E suppressed diet-induced hypercholesterolemia by 23% in the \( \text{ETg}^{+/-}:\text{LDLRKO} \) mice and by 38% in the \( \text{ETg}^{+/-}:\text{LDLRKO} \) mice, even in the absence of the functional LDLR. Lipoprotein analyses showed that the TC contents were reduced in CM+VLDL and in IDL, but not in LDL (Table V).

Figure 4. Plasma kinetics of \(^{125}\text{I-labeled VLDL. VLDL were isolated from either ETg}^{+/-}:\text{LDLRKO} \) or \( \text{ETg}^{+/-}:\text{LDLRKO} \) mice that had been maintained on a normal chow and water supplemented with zinc, by ultracentrifugation at a density of 1.006 g/ml, and refloated at same density. The same lipoprotein preparations as shown in Fig. 1 C were used for radioiodination by iodine monochloride method. Specific activities of labeled lipoproteins were 50–200 cpm/ng protein. 4 \( \mu\text{g} \) protein were injected into the jugular vein of three mice, together with the autologous fraction (\( d > 1.063 \) g/ml) equivalent to the same amount of plasma from which VLDL originated. At the indicated times, blood was collected. Apo B–associated radioactivity was determined using the isopropanol precipitation method as previously described (9). The value at 1 min after injection was used as 100%. The recipients were wild-type mice (A), and autologous \( \text{ETg}^{+/-}:\text{LDLRKO} \) and \( \text{ETg}^{+/-}:\text{LDLRKO} \) mice that had been maintained on a normal chow and water supplemented with zinc (B).

Figure 5. Vitamin A tolerance test. Aqueous retinyl palmitate (2 mg per animal) was administered as a bolus through a gastric cannula to the \( \text{ETg}^{+/-}:\text{LDLRKO} \) (\( \bigcirc \)), \( \text{ETg}^{+/-}:\text{LDLRKO} \) (\( \bullet \)), and \( \text{ETg}^{+/-}:\text{LDLRKO} \) mice (\( \blacktriangle \)) that had been maintained on a normal chow and water supplemented with zinc, after a 4-h fast (\( n = 5 \)). Blood was collected at the indicated times. Plasma levels of retinyl palmitate (\( A \)) and free retinol (\( B \)) were determined in the pooled plasma.
The concentrations of plasma apo B measured by SRID were as follows: 3,055 ± 1,103 mg/dl (n = 6) in the ETg°°°:LDLRKO, 1,505 ± 1,093 mg/dl (n = 8) in the ETg°°°:LDLRKO, and 887 ± 715 mg/dl (n = 11) in the ETg°°°:LDLRKO mice. ETg°°°:LDLRKO and ETg°°°:LDLRKO mice had significantly lower plasma apo B levels than ETg°°°:LDLRKO mice (P < 0.05 and < 0.001, respectively).

Suppression of diet-induced atherosclerosis. We compared the cross-sectional lesion areas in the aortic sinus from the ETg°°°:LDLRKO and ETg°°°:LDLRKO mice after feeding with a 1.25% cholesterol/atherogenic diet (Fig. 6). The lesion areas of the ETg°°°:LDLRKO mice were significantly smaller than those of the ETg°°°:LDLRKO mice by 45% (124,603 ± 41,464 [n = 14] versus 680,51 ± 305,25 mm² [n = 16], P < 0.001).

**Discussion**

The present study has demonstrated that overexpression of apo E reduces plasma cholesterol levels even in the absence of the functional LDLR. The cholesterol lowering appears to result from the reduction of the apo B-100-containing lipoproteins in LDL. From the results of the lipoprotein kinetics studies, we speculate that both the decreased production and the increased clearance of VLDL, but not the changes in chylomicron metabolism, account for the cholesterol-lowering in the LDLRKO mice overexpressing rat apo E. Furthermore, the overexpression of rat apo E suppressed diet-induced hypercholesterolemia as well as atherosclerosis.

We have previously shown that mice overexpressing apo E have decreased levels of plasma TC and TG, and are resistant to diet-induced hypercholesterolemia (13, 14). Lipoproteins kinetics studies showed the increased plasma clearance of lipoproteins such as VLDL and LDL. However, it remains unknown whether the increased clearance of the lipoproteins was mediated through the LDLR. The present study has clearly demonstrated that the overexpression of rat apo E has cholesterol-lowering effects even in the absence of the functional LDLR, indicating that the non-LDLR pathway is also involved in the cholesterol lowering by the apo E transgene.

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**Table IV. Effects of Cholesterol Feeding on the Plasma Lipid Levels**

<table>
<thead>
<tr>
<th>Tg</th>
<th>n</th>
<th>Zn</th>
<th>TC</th>
<th>TG</th>
</tr>
</thead>
<tbody>
<tr>
<td>-/-</td>
<td>15</td>
<td>Before</td>
<td>297±73</td>
<td>121±33</td>
</tr>
<tr>
<td>(8/7)</td>
<td>After</td>
<td>3116±1025</td>
<td>101±59</td>
<td></td>
</tr>
<tr>
<td>+/+</td>
<td>27</td>
<td>Before</td>
<td>284±48</td>
<td>111±28</td>
</tr>
<tr>
<td>(11/16)</td>
<td>After</td>
<td>2394±893ª</td>
<td>73±55</td>
<td></td>
</tr>
<tr>
<td>+/+</td>
<td>15</td>
<td>Before</td>
<td>294±47</td>
<td>131±40</td>
</tr>
<tr>
<td>(6/9)</td>
<td>After</td>
<td>1918±632²</td>
<td>66±40</td>
<td></td>
</tr>
</tbody>
</table>

**Table V. Cholesterol Contents in the Lipoprotein Fraction after Cholesterol Feeding**

<table>
<thead>
<tr>
<th>Tg</th>
<th>CM/VLDL</th>
<th>IDL</th>
<th>LDL</th>
<th>HDL</th>
</tr>
</thead>
<tbody>
<tr>
<td>-/-</td>
<td>968</td>
<td>1010</td>
<td>336</td>
<td>8</td>
</tr>
<tr>
<td>+/-</td>
<td>475</td>
<td>990</td>
<td>362</td>
<td>29</td>
</tr>
<tr>
<td>+/-</td>
<td>284</td>
<td>694</td>
<td>331</td>
<td>48</td>
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</table>

Plasma apo B-100 concentrations were reduced in mice that overexpressed apo E (Fig. 3 and Table III), corroborating the idea that the reduction of non–HDL-C levels is due to a decrease in the particle number of apo B–containing lipoproteins, but not to a decrease in the cholesterol contents in each lipoprotein particle. E+VLDL was enriched with rat apo E compared to E−VLDL (Fig. 1), and cleared faster than E−VLDL when injected into wild-type mice with the functional LDLR (Fig. 4 A), indicating that E+VLDL has higher affinity for the LDLR than E−VLDL. When E−VLDL or E+VLDL were injected back into the LDLRKO mice from which the respective VLDL were isolated (Fig. 4 B), their plasma clearance rates were four- and sixfold slower than the values for the experiments where wild-type mice were used as recipients. These results indicate that the LDLR has overwhelming contribution to the clearance of these lipoproteins. The difference in the plasma clearance between E−VLDL and E+VLDL was not discernible in the initial 3 h, but E+VLDL was cleared faster than E−VLDL after 6 h. As a whole, E+VLDL had higher FCR and lower production rate.
than E–VLDL, even when injected into mice lacking the LDLR.

Apo E secreted from the liver has been thought to be an important determinant of the clearance of lipoproteins. This secretion-recapture model was initially proposed to explain the local autocrine and paracrine-like function of apo E (1, 25), and was subsequently extended to explain the rapid clearance of CR (26). In agreement with this model, the enhanced clearance of E+VLDL via the non-LDLR pathway may, at least in part, reduce the apo B-100 levels in the LDRLKO mice expressing rat apo E. In addition, VLDL production was reduced in these animals. We speculate that nascent VLDL acquires excess apo E in the space of Disse, and then is sequestered onto the surface of the hepatocytes followed by endocytosis through a pathway distinct from the LDLR, presumably LRP or heparan sulfate proteoglycans.

In contrast to our previous report showing that the plasma TG levels were markedly reduced in mice expressing apo E (13), the plasma TG levels in the ETg<sup>+/−</sup>:LDRLKO and ETg<sup>−/−</sup>:LDRLKO were similar to those in the ETg<sup>−/−</sup>:LDRLKO mice. This discrepancy can be explained by assuming that the TG-lowering effect of the apo E transgene requires the LDLR, indicating that the apo E transgene preferentially stimulates the catabolism of TG-rich lipoproteins through the LDLR-mediated pathway.

With respect to chylomicron metabolism, the excision of the plasma retinyl ester after vitamin A load was delayed nine-fold in the LDRLKO mice, compared to wild-type mice (13). These observations are consistent with our previous findings that the LDLR plays a pivotal role in the metabolism of chylomicron (27). In the present study, however, no significant difference was observed in the plasma excursion of retinyl ester between the LDRLKO mice with and without the apo E transgene (Fig. 5), which is apparently contradictory to the changes in the VLDL metabolism. This can be explained by the facts that apo E is not overproduced in the intestine (13), and that the intestine lacks such space for enrichment with apo E as the space of Disse.

Diet-induced hypercholesterolemia was suppressed in the LDRLKO mice overexpressing rat apo E in both a homozygous or heterozygous state (Table IV). In parallel, diet-induced fatty streak lesion formation was suppressed in the ETg<sup>+/−</sup>:LDRLKO mice (Fig. 6). Because the lesion formation and hypercholesterolemia were suppressed to a similar degree, the cholesterol-lowering effects of the apo E transgene may largely account for the antiatherogenic effects.

Recently, we and other investigators have reported that the introduction of genes such as lipoprotein lipase (11), VLDL receptor (28, 29), APOBEC-1 (30), or cholesterol 7α-hydroxylase (31), which are apparently irrelevant to the LDLR, ameliorated hypercholesterolemia in the LDRLKO mice. This kind of strategy may help avoid potential problems such as autoantibody formation against genetically introduced proteins. Pharmaceutical or genetic manipulation of the hepatic apo E production should be a promising adjunctive therapy for homozygous familial hypercholesterolemia.

**Acknowledgments**

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**References**


