Probucol Does Not Affect Lipoprotein Metabolism in Macrophages of Watanabe Heritable Hyperlipidemic Rabbits

Yutaka Nagano, Toru Kita, Masayuki Yokode, Kenji Ishii, Noriaki Kume, Hideo Otani, Hidenori Arai, and Chuichi Kawai

We recently reported that the antioxidant action of probucol inhibited the progression of atherosclerosis in Watanabe heritable hyperlipidemic (WHHL) rabbits. In this study, we investigated another possible action of probucol: Its action as an antiatherogenic agent on macrophages. When WHHL rabbit peritoneal macrophages were pre-incubated in vitro with probucol and then incubated with several atherogenic lipoproteins, the incorporation of the lipoproteins was not significantly prevented. In the case of mouse peritoneal macrophages, pre-incubation with probucol showed slight, although not statistically significant, changes in the amount of lipoprotein incorporations. We also used macrophages obtained from mice and WHHL rabbits fed with probucol, but the amount of uptake of lipoproteins by these cells was not less than that by control macrophages. Furthermore, to investigate the incorporation of atherogenic lipoproteins into these cells, we prepared probucol-containing macrophages; however, probucol in macrophages failed to prevent the uptake of such lipoproteins. In conclusion, probucol did not prevent foam cell transformation of macrophages of WHHL rabbit or mice directly, and the effect of probucol against atherogenesis in WHHL rabbits was due mainly to its inhibitory effect on the oxidative modification of low density lipoprotein, as previously reported. (Arteriosclerosis 9:453-461, July/August 1989)
Company, Tokyo, Japan). The rabbits were fed rabbit laboratory chow RM-1 (Oriental Yeast Company).

Materials

1-14C-oleic acid (57.0 mCi/mMol) and cholesteryl-1,2,6,7-3H-N-oleate (75.3 Ci/mMol) were obtained from New England Nuclear (Boston, MA). Bovine serum albumin (BSA) was from Armour Pharmaceutical Company (Kankakee, IL). 1-14C-oleic acid-BSA complex was prepared as described.13 Fetal calf serum (FCS), obtained from Flow Laboratories (Mclean, VA), was inactivated at 56°C for 30 minutes before use. Lactalbumin hydrolysate was purchased from Gibco Laboratories (Chargin Falls, OH). L-Glutamine and streptomycin-penicillin solutions were from Flow Laboratories (North Ryde, N.S.W., Australia). Dulbecco’s Modified Eagle’s Medium (DMEM) and Dulbecco’s phosphate-buffered saline (PBS) were purchased from Nissui Pharmaceutical Company, Limited (Tokyo, Japan). Plastic Petri dishes were obtained from Nunc (Roskilde, Denmark), and liquid paraffin oil was from Nakarai Chemical Company (Kyoto, Japan). Other chemicals were reagent grade.

Preparation of Probucol Diet

Pure probucol powder kindly supplied by Daiichi Pharmaceutical Company Limited (Tokyo, Japan) was simply added to the raw animal chow at the rate of 1% (wt/wt). No organic solvent was used. Then the chow was ground to the appropriate size for the animals.

Administration of Probucol

Six WHHL rabbits (ages 2 to 4 months in the probucol treatment group, Group P) were started on 100 g/day of chow containing 1% (wt/wt) of probucol. Six control WHHL rabbits (ages 2 to 4 months, Group C) were started on the same amount of standard rabbit chow. One month later, we checked the plasma concentrations of probucol in the Group P rabbits. The value was 98.9±22.7 μg/ml (mean±SD), which already exceeded the level that we previously reported after 6 months of probucol feeding (42.9±8.0 μg/ml).11 Because most probucol in plasma exists in particles of lipoproteins,14 it was expected that probucol had already exerted enough influence on the LDL of these rabbits by this time. Based on these observations, LDL prepared from the blood of WHHL rabbits fed probucol for more than 1 month was used as the probucol-treated LDL. For the experiments, we used LDL prepared from both groups of WHHL rabbits before they were 10 months old.

In some experiments, we used macrophages obtained from probucol-fed animals. To obtain peritoneal macrophages from probucol-fed WHHL rabbits, we fed the rabbits the probucol diet more than 1 month, considering the plasma concentration of probucol as stated above. We also obtained peritoneal macrophages from probucol-fed mice. For this purpose, mice ages 6 to 7 weeks were started on mouse chow enriched with 1% probucol (wt/wt). Before obtaining the macrophages, we measured the concentrations of plasma cholesterol and probucol of mice at 2, 4, and 8 weeks after beginning the diet, and we determined the sufficient period of probucol feeding for the mice. Because the amount of plasma obtained from one mouse was too small for all the experiments, and because macrophages obtained from mice were gathered in one tube and then dispersed onto dishes, we pooled the plasma of 10 mice and used this to measure the concentrations of probucol and plasma lipids. The mice consumed an unrestricted amount of chow.

Preparation of Macrophase Monolayers

Peritoneal macrophages from a WHHL rabbit were prepared by the method described by Ishii et al.15 First, liquid paraffin oil (40 ml/rabbit) was injected into the peritoneal cavity of a WHHL rabbit. Four days later, cells were harvested by peritoneal lavage with 500 ml of saline under anesthesia with pentobarbital. The cells were collected by centrifugation (1500 rpm for 10 minutes at 4°C), were washed once with 30 ml of saline, and were suspended in DMEM containing 0.2% (wt/vol) lactalbumin hydrolysate,16 penicillin (100 U/ml), and streptomycin (100 μg/ml) at a final concentration of 2×10⁶ cells/ml. Aliquots (1 ml) of this cell suspension were dispersed onto plastic Petri dishes (35×10 mm) and were incubated in a humidified CO₂ (5%) incubator at 37°C for 2 hours. Then each dish was washed twice with 2 ml of DMEM to remove nonadherent cells. After the monolayers were incubated for 18 hours at 37°C with 1 ml of DMEM containing 0.2% lactalbumin hydrolysate in the incubator, the cells were washed twice with 2 ml of DMEM and then used for the experiments.

In the mice, peritoneal cells harvested from unstimulated mice were pooled in PBS as described by Kita et al.17 The incubation of cells was performed with the same procedure as described above for rabbit peritoneal macrophages except that the population of cells dispersed per dish was 3×10⁶, and 10% FCS (vol/vol) was used instead of 0.2% lactalbumin hydrolysate.

In some experiments, macrophages were brought into contact with probucol during the 18 hours of pre-incubation time. In these cases, 5 μl of the stock solution of probucol (1 or 10 mg/ml dissolved in ethanol) was added to 1 ml of DMEM containing 10% FCS (final concentration, 5 or 50 μg/ml, respectively) and this was incubated for 18 hours, then washed twice with 2 ml of DMEM, and used for the experiments. Pre-incubation time was 18 hours because a previous study of the in vitro effects of probucol18 had shown that probucol had a significant effect on macrophages within 12 hours of incubation. The viability of the cells was checked after pre-incubation by using trypan blue dye. More than 99% of the cells in each dish excluded the pigment regardless of whether probucol or ethanol was present in the pre-incubation medium.

Probucol Concentration

When we used macrophages from probucol-fed animals or from control animals incubated with probucol-containing lipoproteins, the concentrations of probucol in macrophages were also measured. For this purpose, macrophages incubated under each condition were collected by a rubber policeman (Costar, Cambridge, MA, Catalog No. 3010), were centrifuged at 1500 rpm for
10 minutes, and were dissolved with 0.2 N NaOH. An aliquot of this solution was used to determine the probucol concentrations in macrophages. The amount of probucol in saline used for peritoneal lavage and that in the media used to cultivate macrophages of probucol-fed animals were also measured.

To measure the concentration of probucol, the lipid fraction was extracted from samples with ethanol and diethyl ether, then dissolved with methanol, and analyzed with high-performance liquid chromatography.

**Lipoproteins**

To take LDL from the WHHL rabbits, blood was obtained from ear arteries of WHHL rabbits in both groups with ethylenediamine tetraacetic acid (EDTA) disodium as an anticoagulant. LDL (d=1.019 to 1.063) was isolated from plasma by ultracentrifugation and was dialyzed against two changes of at least a 500-fold volume of 150 mM NaCl containing 0.24 mM EDTA (pH 7.4). LDL was also isolated from the plasma of normal Japanese White rabbits as described earlier.19 Acetyl LDL was prepared from the LDL of healthy human subjects or from both groups of WHHL rabbits by the method described by Basu et al.20 For the oxidation of LDL, 150 μg of LDL dialyzed with PBS19 was suspended in 1 ml of PBS containing 0.5 μM CuSO4 and was incubated at 37°C for 24 hours in a CO2 incubator. Beta-very low density lipoprotein (β-VLDL) was isolated as the d<0.106 fraction of a Japanese White rabbit fasted overnight after being fed a 2% cholesterol and 10% corn-oil diet for more than 14 days.17

**Assays of Cholesterol Reacylation**

To initiate the experiment, 0.6 ml of DMEM and 27 μg of lipoprotein were added to the prepared macrophage monolayers (final concentration, 45 μg/ml). This was incubated in a humidified CO2 incubator (5%) at 37°C. We followed the method described by Brown et al.7 except that the serum was omitted from the incubation medium.21 Lactalbumin hydrolysate was not added to the medium of the WHHL rabbit macrophages during the incubation time. Cellular cholesteryl esters were isolated by thin-layer chromatography, and the cholesteryl 4C-oleate content was determined by liquid scintillation counting with 2H-cholesteryl oleate as an internal standard.8 The data were obtained by averaging duplicate incubations.

**Oil Red O Staining**

Monolayers of peritoneal macrophages were prepared on a Slide Flask (Nunc, Roskilde, Denmark, Catalogue No. 170920) and were incubated with lipoproteins in DMEM containing 10% FCS for 24 hours. Then the cells were dried, fixed with 6% formalin for 5 minutes, stained with oil red O for 60 minutes, and counterstained with Meyer's hamatoxylin for 10 minutes.

**Other Measurements**

Serum levels of cholesterol were measured with an enzymatic method with a Choles Color Ace kit from the Ono Pharmaceutical Company, Limited (Osaka, Japan). The cholesterol levels in the subfractions of lipoprotein were measured after they had been isolated by ultracentrifugation.
Figure 1. Effect of in vitro addition of probucol on cholesteryl ester formation in peritoneal macrophages of Watanabe heritable hyperlipidemic (WHHL) rabbits by several lipoproteins. Macrophages were brought into contact with ethanol or probucol dissolved in ethanol during an 18-hour pre-incubation. The cells were washed twice with 2 ml of Dulbecco's Modified Eagle's Medium (DMEM). To each monolayer (2x10^6 cells), 0.6 ml of DMEM containing 0.2 mM [14C]-oleate-albumin, and several lipoproteins (45 μg/ml) were added, and the cells were incubated for 6 hours at 37°C. The amount of cholesteryl [14C]-oleate formed in cells pre-incubated under each condition was reported as a percentage of that formed in cells that underwent control pre-incubation. The mean values of cholesteryl ester formation in control WHHL rabbit macrophages by acetylated low density lipoprotein (acetylated LDL), beta-very low density lipoprotein (β-VLDL), and oxidized LDL were 22.9, 12.1, and 8.4 nmol/mg protein, respectively, these data are shown as 100% in the figures. The letters at the bottom represent the conditions of pre-incubation: C=control pre-incubation, E=5 μl ethanol added to 1 ml of medium, P=5 μl of ethanol solution of probucol (1 mg/ml) added to 1 ml of medium (final concentration of probucol: 1 mg/ml), P0=5 μl of ethanol solution of probucol (10 mg/ml) added to 1 ml of medium (final concentration of probucol: 50 μg/ml).

Figure 2. Effect of in vitro addition of probucol on cholesteryl ester formation in peritoneal macrophages of mice by several lipoproteins. Macrophages were brought into contact with ethanol or probucol dissolved in ethanol during an 18-hour pre-incubation. The cells were washed twice with 2 ml of Dulbecco's Modified Eagle's Medium (DMEM). To each monolayer (3x10^6 cells), 0.6 ml of DMEM containing 0.2 mM [14C]-oleate-albumin, and several lipoproteins (45 μg/ml) were added, and the cells were incubated for 6 hours at 37°C. The amount of cholesteryl [14C]-oleate formed in cells pre-incubated under each condition was reported as a percentage of that formed in cells that underwent control pre-incubation. The mean values of cholesteryl ester formation in control mouse peritoneal macrophages by acetylated low density lipoprotein (acetylated LDL), beta-very low density lipoprotein (β-VLDL), and oxidized LDL were 50.6, 39.9, and 4.9 nmol/mg protein, respectively; these data are shown as 100% in the figure. See the legend for Figure 1 for an explanation of the abbreviations.

Figure 3. Effect of several lipoproteins on cholesteryl ester formation in macrophages obtained from probucol-treated Watanabe heritable hyperlipidemic (WHHL) rabbits. Rabbits were fed a probucol diet (1%, wt/wt) for more than 1 month. To each monolayer (2x10^6 cells), 0.6 ml of Dulbecco's Modified Eagle's Medium (DMEM) containing 0.2 mM [14C]-oleate-albumin, and several lipoproteins (45 μg/ml) were added; this was incubated at 37°C for 6 hours. The values of cholesteryl [14C]-oleate formation in probucol-fed WHHL rabbit macrophages are given as a percentage of those in control WHHL rabbit macrophages. The mean values of cholesteryl ester formation in these experiments with acetylated low density lipoprotein (acetylated LDL), beta-very low density lipoprotein (β-VLDL), and oxidized LDL were 19.5, 13.4, and 7.7 nmol/mg protein, respectively, in control macrophages. These data are reported as 100% in the figure. C=control WHHL rabbit, P=probucol-fed WHHL rabbit.

The same experiment was performed with macrophages obtained from mice fed with probucol. Beforehand, we determined the adequate period of probucol feeding for mice. In Table 2, the mean plasma concentrations of cholesterol and probucol in probucol-fed mice are shown. The plasma levels of cholesterol dropped significantly only 2 weeks after the start of the feeding, and no further decrease was observed during the next 6 weeks. The plasma concentration of probucol showed similar levels at 2, 4, and 8 weeks after feeding was begun. Therefore, in this experiment we used the macrophages of mice fed probucol for more than 2 weeks.
We found that probucol prevented the progression of atherosclerosis in WHHL rabbits without marked reduction of plasma cholesterol levels in vivo. It has been suggested that peroxi-
dized lipids are closely related to the initiation and pro-
gression of atheromatous plaque formation.25,26,27 In addition, cell-modified (oxidized) LDL in which acyl chains were peroxidized has reportedly transformed macro-
phages into foam cells in vitro.28-37 Foam cells have been rec-
ognized as a characteristic feature in the initial stage of
atherosclerosis.1 As previously reported, LDL obtained from patients treated with probucol were resistant against oxidative modification in vitro,10 and we confirmed this in LDL obtained from WHHL rabbits.11

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Table 2. Effect of Probucol Feeding on Plasma Level Values of Cholesterol and Probucol in Mice

<table>
<thead>
<tr>
<th>Duration of treatment</th>
<th>TC</th>
<th>HDL-C</th>
<th>LDL-C</th>
<th>VLDL-C</th>
<th>Probucol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>123</td>
<td>82</td>
<td>29</td>
<td>12</td>
<td>ND</td>
</tr>
<tr>
<td>2 weeks</td>
<td>39</td>
<td>21</td>
<td>10</td>
<td>8</td>
<td>11.1</td>
</tr>
<tr>
<td>4 weeks</td>
<td>40</td>
<td>19</td>
<td>9</td>
<td>12</td>
<td>9.5</td>
</tr>
<tr>
<td>8 weeks</td>
<td>46</td>
<td>20</td>
<td>11</td>
<td>15</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Values are mg/dl except probucol, which is μg/ml. The data were obtained from plasma pooled from 10 mice. Consequently, the mean values of the 10 mice in each group are shown. Abbreviations are given in the footnote to Table 1.

However, Figure 4 shows that probucol feeding did not prevent the foam cell transformation of mouse macrophages.

Figure 5 shows that acetyl LDL modified from P-LDL (acetyl P-LDL) was significantly incorporated by mouse peritoneal macrophages, showing saturation kinetics. The amount of cholesteryl ester synthesis in macrophages stimulated by acetyl P-LDL was almost the same as acetyl LDL modified from LDL of probucol-fed Watanabe heritable hyperlipidemic rabbits (acetyl P-LDL) on cholesteryl ester formation in mouse peritoneal macrophages. To each monolayer (3×10^6 cells), 0.6 ml of Dulbecco's Modified Eagle's Medium (DMEM) containing 0.2 mM 14C-oleate-albumin, and several lipoproteins (45 μg/ml) were added and incubated at 37°C for 6 hours. The values of cholesteryl 14C-oleate formation in probucol-fed mouse macrophages are given as a percentage of those in control mouse macrophages. The mean values of cholesteryl ester formation in these experiments by acetylated low density lipoprotein (acetyl LDL), beta-very low density lipoprotein (β-VLDL), and oxidized LDL were 47.0, 32.1, and 3.9 nmol/mg protein, respectively, in control macrophages. These data are reported as 100% in the figure. C=control mouse, P=probucol-fed mouse.

Discussion

Recently we11 and Carew et al.12 have ascertained that probucol prevented the progression of atherosclerosis in WHHL rabbits without marked reduction of plasma cholesterol levels in vivo. It has been suggested that peroxi-
dized lipids are closely related to the initiation and pro-
gression of atheromatous plaque formation.25,26,27 In addition, cell-modified (oxidized) LDL in which acyl chains were peroxidized has reportedly transformed macro-
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atherosclerosis.1 As previously reported, LDL obtained from patients treated with probucol were resistant against oxidative modification in vitro,10 and we confirmed this in LDL obtained from WHHL rabbits.11

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Figure 6. Light microscopic appearances of mouse peritoneal macrophages incubated with acetylated low density lipoproteins (acetyl LDL) modified from LDL of probucol-treated Watanabe heritable hyperlipidemic (WHHL) rabbit (A), acetyl LDL modified from LDL of control WHHL rabbit (B), and LDL obtained from control WHHL rabbit (C). Aliquots of lipoprotein (45 μg/ml) were added to monolayers of macrophages and incubated for 24 hours in a CO₂ incubator at 37°C. Staining was performed with oil red O and Meyer's hematoxylin as described in the text. ×970
whether the uptake of atherogenic lipoproteins, such as WHHL rabbits with probucol in vitro, then examined acetyl LDL, 0-VLDL, or oxidized LDI could be inhibited. We used probucol in several ways in our experiments. Transformation into foam cells. To investigate this, we probucol could act on macrophages and prevent their transformation into foam cells. Furthermore, we carried out experiments using macrophages into which probucol was definitely incorporated. First, we pre-incubated mouse peritoneal macrophages with acetyl P-LDL, which contained probucol with the concentration of 10.3 μg/mg protein. However, as shown in Figure 1, there was no statistically significant difference between the control and probucol-treated macrophages in the mean amount of cholesteryl ester synthesis stimulated by acetyl LDL, β-VLDL, and oxidized LDL.

Yamamoto et al. 18 have reported that in vitro addition of probucol into culture medium prevented the foam cell transformation of human macrophage-like cells (UE-12) by acetyl LDL to at least a half level of control incubation. However, we could not confirm such a drastic change in our experimental system. It is possible that the different results were caused by the different species of cells used. We used cells from WHHL rabbits because it was in this animal that probucol has been definitely effective on the prevention of atherogenesis. So we regard this study as a counterpart of our previous report. 11 As shown in Figure 2, the addition of probucol to mouse peritoneal macrophages in vitro caused a response that was slightly different from the case of WHHL rabbit macrophages, although the changes were not significant.

We also tried the pre-incubation with a higher concentration level (200 μg/ml) of probucol, the level at which Yamamoto et al. proved the effect of probucol on macrophages. However, this nonphysiological concentration of probucol caused no significant inhibition or stimulation of lipoprotein uptake by macrophages (data not shown). This can be explained by the fact that probucol is very hydrophobic, so an excessive amount of probucol is not soluble in the culture medium and could not exert any further influence.

Because most probucol in plasma does not exist in free form but mainly in the particle of lipoproteins, 14 it cannot be expected that probucol in vivo acts on macrophages in the same manner as in the in vitro experiments. For this reason, we investigated the possibility that macrophages obtained from probucol-fed animals might have been affected by probucol in vivo by mechanisms different from those in the in vitro experiments described above.

To make this point clear, we performed experiments with macrophages obtained from probucol-fed WHHL rabbits and mice. The concentration of probucol was detectable in the saline used for peritoneal lavage of probucol-fed WHHL rabbit (0.2 μg/ml). This suggested that these macrophages had contacts with probucol in vivo, although the concentration of probucol in macrophages themselves was not detectable by our system. As stated previously, oxidized LDL is the most likely atherogenic lipoprotein that exists in vivo and is thought to play the most important role in the atherogenesis of WHHL rabbits. However, foam cell transformation of macrophages by oxidized LDL was not affected by probucol feeding, although the behavior of cholesteryl ester synthesis in WHHL macrophages by other lipoproteins was slightly different, as shown in Figure 3. Figure 4 also revealed no in vivo effect of probucol on mouse peritoneal macrophages.

Table 3. Effect of Cell-associated Probucol on Incorporation of Lipoprotein

<table>
<thead>
<tr>
<th>Cholesterol ester formed in macrophages (nmol/mg protein)</th>
<th>Lipoprotein used for 18-hour pre-incubation</th>
</tr>
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<tbody>
<tr>
<td>After 18 hours of pre-incubation</td>
<td>Acetyl C-LDL</td>
</tr>
<tr>
<td>43±3</td>
<td>54±10</td>
</tr>
<tr>
<td>After additional 30 hours of incubation with</td>
<td>Acetyl LDL</td>
</tr>
<tr>
<td></td>
<td>β-VLDL</td>
</tr>
<tr>
<td></td>
<td>Oxidized LDL</td>
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</table>

Monolayers of mouse peritoneal macrophages (3×106 cells) were incubated in 0.6 ml of Dulbecco's Modified Eagle's Medium (DMEM) containing 10% fetal calf serum (FCS), 0.2 mM 14C-oleate-albumin, and 100 μg/ml of acetylated low density lipoprotein (acetyl LDL) modified from LDL obtained from control Watanabe heritable hyperlipidemic (WHHL) rabbits (C-LDL) (acetyl C-LDL) or from LDL obtained from probucol-treated WHHL rabbits (P-LDL) (acetyl P-LDL) for 16 hours. Cells in some dishes were harvested at this time to measure the amount of cholesteryl 14C-oleate formed. Other cells were washed twice with 2 ml of DMEM and received 0.6 ml of fresh DMEM containing 10% FCS and 0.2 mM 14C-oleate albumin. Then 100 μg/mg of acetyl LDL modified from LDL of healthy human subjects, beta-very low density lipoprotein (β-VLDL) obtained from rabbits fed with a 2% cholesterol/10% com oil-enriched diet, or oxidized LDL modified from rabbit LDL was added, and this was incubated for 30 hours. Probucol concentrations in macrophages were measured as follows: 3×106 cells were dispersed onto plastic Petri dishes (100x20 mm) and were incubated with 6 ml of DMEM containing 10% FCS for the same period as for cells incubated to measure the cholesteryl ester formation. At the end of the incubation time, the cells were harvested, centrifuged, and dissolved with 0.2 N NaOH to measure protein contents and concentrations of probucol in macrophages. Probucol concentrations in macrophages pre-treated with acetyl P-LDL were 0.37 μg/mg protein at the end of 18 hours pre-incubation and 0.4, 0.36, and 0.38 μg/mg protein after an additional 30 hours of incubation with acetyl LDL, β-VLDL, or oxidized LDL, respectively.

Table 1 shows that the plasma levels of total cholesterol did not decrease as expected after 4 months of probucol. We do not know the reason for the lack of cholesterol lowering in WHHL rabbits, but recent reports showed the same tendency. 11,12 This strongly suggests that the antiatherogenic action of probucol is caused by a mechanism different from its cholesterol-lowering effect. The changes in the values of cholesterol substractions might be due to a decrease in triglycerides. According to Watanabe, 38 the plasma levels of triglyceride in WHHL rabbits drop without drugs as they get older. This may have caused the decrease in triglyceride-rich VLDL and the relative increase of LDL in our study.

Many investigators are interested in whether probucol prevents atherogenesis with a mechanism other than as an antioxidant. In the present study, we used materials from WHHL rabbits to investigate the possibility that probucol could act on macrophages and prevent their transformation into foam cells. To investigate this, we used probucol in several ways in our experiments.

First, we pre-incubated the peritoneal macrophages of WHHL rabbits with probucol in vitro, then examined whether the uptake of atherogenic lipoproteins, such as acetyl LDL, β-VLDL, or oxidized LDL, could be inhibited.
acetyl P-LDL was significantly incorporated into macrophages, although P-LDL, which contained probucol with the concentration of 9.1 μg/mg protein, was hardly incorporated. Figure 6A shows the macrophages transformed into foam cells by incubation with acetyl P-LDL. Foam cell transformation was observed in the cells of Figure 6A to the same degree as those of Figure 6B, which were incubated with acetyl C-LDL. In contrast, the cells in Figure 6C, which were incubated with C-LDL, were virtually devoid of lipid droplets. The probucol concentration in macrophages incubated with acetyl P-LDL was 0.37 μg/mg cellular protein, but probucol was not detectable in macrophages incubated with P-LDL, in spite of the similar levels of probucol concentrations in the medium. Thus, we confirmed that probucol was incorporated into macrophages as a component of acetyl P-LDL during the pre-incubation. Then we washed the medium completely and added acetyl LDL modified from human LDL, rabbit β-VLDL, or oxidized LDL in renewed medium and continued the incubation. The results in Table 3 show that, even when macrophages contain probucol, they show additional incorporation of atherogenic lipoproteins. There was no significant difference in the amount of this additional incorporation between macrophages pre-incubated with acetyl P-LDL and those pre-incubated with acetyl C-LDL, which was devoid of probucol. We also performed the same experiments with WHHL rabbit macrophages. The mean values of additional cholesteryl ester synthesis stimulated by acetyl LDL, β-VLDL, and oxidized LDL in WHHL rabbit macrophages pre-incubated with acetyl C-LDL were 127.9, 68.1, and 48.3 nmol/mg protein; those in macrophages pre-incubated with acetyl P-LDL were 121.4, 69.3, and 45.2 nmol/mg protein, respectively. These data indicated that probucol did not have an effect on macrophages for the prevention of foam cell transformation even when it was definitely incorporated into macrophages.

Our data in the studies above prove that probucol did not significantly prevent macrophages from transforming into foam cells, which is an important event in the early stage of atherogenesis. Considering these results and our previous study,11 we now think that the action of probucol as an antioxidant and as an antiatherogenic agent is tightly connected. Thus, the strong possibility of the existence of oxidized LDL in vivo could be one answer to the paradoxical question. How can lipoprotein-bound cholesteryl esters accumulate in the macrophages of WHHL rabbits and homozygous familial hypercholesterolemia patients who have no LDL receptor?

Acknowledgments

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Index Terms: probucol • oxidized LDL • macrophages • foam cell transformation • atherosclerosis • lipid peroxides • WHHL rabbit
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