Effects of cholesterol feeding on synthesis and metabolism of cholesterol and bile acids in germfree rats

Bengt E. Gustafsson, Bo Angelin, Kurt Einarsson, and Jan-Åke Gustafsson

Department of Germfree Research, Department of Medicine, Serafimerlasarettet, and Department of Chemistry, Karolinska Institutet, Stockholm, Sweden

Abstract The aim of the present investigation was to study the influence of cholesterol feeding on cholesterol synthesis and fecal excretion of bile acids in germfree rats. Four germfree rats were fed a basal diet containing 0.004% cholesterol and four germfree rats received the same diet supplemented with 0.4% cholesterol for 2 weeks. Cholesterol synthesis was studied by assaying the HMG CoA reductase activity in the liver microsomal fraction. Cholesterol feeding decreased the HMG CoA reductase activity from $28.5 \pm 6.6$ (mean $\pm$ SEM) to $9.1 \pm 0.7$ pmol/mg protein per min. In another experiment four germfree rats received the basal diet and four germfree rats the cholesterol-enriched diet. After 6 weeks feces were collected in two 4-day pools for analysis of bile acids. The main fecal bile acids were cholic acid and $\beta$-muricholic acid (a metabolite of chenodeoxycholic acid), comprising more than 95% of total bile acids. Cholic acid was increased from $3.9 \pm 0.2$ to $9.9 \pm 1.2$ mg/kg body weight per day and $\beta$-muricholic acid from $6.6 \pm 0.5$ to $21.8 \pm 3.1$ mg/kg body weight per day. The percentage of cholic acid decreased from $37.1 \pm 1.1$ to $31.2 \pm 1.0\%$. In conclusion, germfree rats like conventional rats have the ability to compensate for an increased input of dietary cholesterol by inhibition of cholesterol synthesis and stimulation of bile acid synthesis. The synthesis of chenodeoxycholic acid (implied from the fecal excretion of $\beta$-muricholic acid) is stimulated to a greater extent than that of cholic acid.

Supplementary key words HMG CoA reductase · cholic acid · chenodeoxycholic acid · $\beta$-muricholic acid

The hepatic cholesterol concentration in germfree rats has been reported to be higher than in conventional rats (1, 2). This accumulation of cholesterol in germfree animals may be explained by a more efficient absorption from the intestine (3) and by a decreased fecal excretion of bile acids and neutral steroids (4, 5). The synthesis of cholesterol, on the other hand, is depressed in germfree rats compared with conventional rats (6). Addition of moderate amounts of cholesterol to the diet tends to higher levels of tissue cholesterol in germfree rats than in conventional rats (7). Thus, it would seem as if the intestinal microflora to some extent protects against increased tissue cholesterol levels in response to dietary cholesterol.

Feeding a high cholesterol diet to conventional rats increases the absorption of cholesterol (8, 9). In answer to this high cholesterol input, the hepatic cholesterol synthesis is inhibited and the catabolism of cholesterol to bile acids is increased (9-11). These mechanisms are not completely compensatory and a certain accumulation of cholesterol occurs in the liver (9, 12). The question may now be asked whether the higher hepatic concentration of cholesterol in livers of germfree rats than in livers of conventional rats may be explained by a deficient compensation in germfree rats to the augmented intestinal input of cholesterol. We have recently shown that the 7a-hydroxylase, which is a rate-determining enzyme in the formation of bile acids from cholesterol, is enhanced to about the same degree in germfree and in conventional rats during cholesterol feeding, indicating that germfree rats would have the ability to increase the synthesis of bile acids (2, 13). However, these in vitro experiments were not correlated with any simultaneous measurements of fecal bile acids.

To obtain further insight into the mechanisms behind the differences in hepatic cholesterol concentration between germfree and conventional rats, we have administered cholesterol to germfree rats

Abbreviations: TLC, thin-layer chromatography; GLC, gas-liquid chromatography; HMG, 3-hydroxy-3-methylglutaryl; HMG CoA reductase, mevalonate:NADP oxidoreductase, EC 1.1.1.34; cholic acid, 3a,7a,12a-trihydroxy-5$\beta$-cholanic acid; chenodeoxycholic acid, 3a,7a-dihydroxy-5$\beta$-cholanic acid; 3a,6$\beta$,7a-trihydroxy-5$\beta$-cholanic acid; $\beta$-muricholic acid, 3a,6$\beta$,7a,8$\beta$-trihydroxy-5$\beta$-cholanic acid.

1 Send reprint requests to Dr. Bengt E. Gustafsson, Department of Germfree Research, Karolinska Institute, Stockholm, Sweden.

2 Dr. Angelin and Dr. Einarsson.

3 Dr. J-A. Gustafsson.
and determined the activity of HMG CoA reductase, which is a rate-determining enzyme in cholesterol synthesis. In addition, the effect of cholesterol feeding on the excretion of fecal bile acids in germfree rats was studied. No attempt was made to perform comparative studies on the effect of cholesterol feeding on the excretion of fecal bile acids in conventional rats. Such a comparison would be very complicated, because, in these animals, bile acids are metabolized to a spectrum of secondary bile acids and, possibly, also to nonsteroidal derivatives (14, 15) by the intestinal microorganisms. This makes quantification of total fecal bile acids complicated. In feces from germfree rats, on the other hand, cholic acid and β-muricholic acid comprise more than 95% of the total bile acids, which simplifies a quantitative analysis. For these reasons, cholesterol effects on fecal bile acids were studied only in germfree rats.

**MATERIALS**

[3-14C]HMG CoA (sp act 20 µCi/mg) and [3-5H](N)mevalonic acid (dibenzylethylene-diamine salt, sp act 25 µCi/mg) were purchased from New England Nuclear Corp., Boston, MA. The radioactive HMG CoA was diluted with unlabeled material, obtained from P-L Biochemicals, Inc., Milwaukee, WI, to yield a sp act of 1.45 µCi/mg. Unlabeled mevalonic acid lactone, NADP, glucose-6-phosphate, and glucose-6-phosphate dehydrogenase were obtained from Sigma Chemical Co., St. Louis, MO.

**METHODS**

**Animals and preparation of microsomes**

Germfree male rats of the Sprague-Dawley strain weighing 200–300 g were used. They were reared according to the technique of Gustafsson (16, 17). They were fed a semisynthetic diet ad libitum with 10% (w/w) arachis oil as the source of fat and supplemented with 0.4% cholesterol (17). Control groups of germfree rats were given the same diet as the experimental groups but with the exclusion of additional cholesterol. This latter diet contained 0.004% cholesterol.

In one experiment, four germfree rats received the basal diet and four germfree rats the cholesterol-enriched diet. After the rats were fed the experimental diets for 6 weeks, feces were collected in two 4-day pools and were stored at −20°C until analyzed. This long feeding time was chosen since germfree rats have a very long transit time of intestinal contents; consequently, following a change in diet, it will take several weeks until a new steady state in bile acid metabolism is reached and the quantity of the fecal bile acids excreted corresponds to the amount of newly synthesized bile acids (19).

**Assay of HMG CoA reductase activity**

The assay system used was similar to that described by Shefer et al. (20). The complete system contained in a volume of 0.85 ml: 0.2 ml of microsomal fraction; phosphate buffer, pH 7.2, 100 mM; NADP, 3 mM; glucose-6-phosphate, 10 mM; glucose-6-phosphate dehydrogenase, 5 enzyme units, [3-14C]HMG CoA, 0.2 mM. The incubation was carried out for 15 min at 37°C. It was stopped by the addition of 0.1 ml of 5 M HCl. Tritium-labeled mevalonic acid (0.01 µCi) and 3 mg of unlabeled mevalonic acid lactone were added as internal standards and the incubation was further shaken for 30 min at 37°C. After cooling to room temperature, 0.5 ml of absolute ethanol was added and the mixture was dried over anhydrous Na2SO4. The solution was extracted three times with 3 ml of ethyl ether. The ethyl ether fractions were combined, dried over anhydrous Na2SO4 and evaporated. The residue of the extract was dissolved in acetone and subjected to TLC with benzene–acetone 1:1 (v/v) as solvent. The thin-layer plate was sprayed with a 0.2% (w/v) solution of 2,7-dichlorofluorescein in methanol and the band corresponding to mevalonic acid lactone was located under UV light. This band was scraped off into a counting vial. The radioactivity was determined in a Packard liquid scintillation spectrometer model.
using Instagel as a scintillator liquid. Corrections were made for quenching and for losses during extraction and TLC by the internal standard. The recovery of tritium-labeled internal standard was about 50%.

**Analysis of fecal bile acids**

Feces were disintegrated in water and refluxed in 70% (v/v) aqueous ethanol for 2 hr. After filtration, the residue was refluxed in chloroform–methanol 1:1 (v/v) for 2 hr. The extracts were combined and an aliquot (1/10 or 1/5) was further hydrolyzed with 1 M KOH in 50% aqueous ethanol for 12 hr at 110°C. The saponification mixture was extracted with hexane, which was discarded. The mixture was then acidified with 6 M HCl and extracted with ethyl acetate. The ethyl acetate was washed with water until neutral and the solvent was evaporated. [14C]Cholic acid was used as an internal standard in the extraction procedure for the correction for losses. The recovery amounted to about 85%.

The residue of the ethyl acetate extract was methylated with diazomethane, silylated, and analyzed by GLC using 1% HiEff 8 BP as the stationary phase.

**RESULTS**

**HMG CoA reductase activity**

The amount of formed mevalonic acid lactone was expressed as pmol/mg protein per min. In the germ-free rats fed the basal diet the reductase activity averaged 28.5 ± 6.6 (mean ± SEM) pmol/mg protein per min (Table 1). In the cholesterol-fed rats the reductase activity was depressed to 9.8 ± 0.7 pmol/mg protein per min (P < 0.05).

**Fecal bile acids**

The two dominating bile acids in feces from germ-free rats were cholic acid and β-muricholic acid. These two bile acids comprised more than 95% of total fecal bile acids in both dietary groups of rats. Small amounts of chenodeoxycholic acid and α-muricholic acid were identified but they were not included in the calculations of total bile acids. Table 2 summarizes the results when germ-free rats were given dietary cholesterol. Cholic acid increased 2.5 times from 3.9 ± 0.2 mg to 9.9 ± 1.2 mg. β-Muricholic acid similarly increased threefold from 6.6 ± 0.5 mg to 21.8 ± 3.1 mg. The sum of cholic acid and β-muricholic acid increased threefold. The percentage of cholic acid decreased significantly (P < 0.005) from 37.1 ± 1.1% to 31.2 ± 1.0%.

**DISCUSSION**

The response to dietary cholesterol is different in various species. Feeding a high cholesterol-containing diet to man causes an increased absorption, a depressed endogenous synthesis of cholesterol, and an enhanced fecal excretion of neutral steroids (21, 22). Feeding cholesterol to the rat also increases the absorption of cholesterol and inhibits cholesterol synthesis in the liver, whereas the fecal excretion of neutral steroids is only slightly increased (8–10). The rat makes up for a high input of cholesterol mainly by an enhanced breakdown of cholesterol to bile acids (9, 11). The present results show that germ-free rats, in conformity with conventional rats, compensate an increased intake of cholesterol by inhibition of hepatic cholesterol synthesis and increased excretion of fecal bile acids.

By far the dominating fecal bile acids in germfree rats are cholic acid and β-muricholic acid (4, 23). The major bile acids formed in the liver are cholic acid and chenodeoxycholic acid (for a review, see ref. 24). The first step in the conversion of cholesterol into bile acids is 7α-hydroxylation, which is rate determining. 5-Cholestene-3β,7α-diol is further converted to 7α-hydroxy-4-cholesten-3-one which is a key intermediate in bile acid biosynthesis. In cholic acid formation 7α-hydroxy-4-cholesten-3-one is 12α-hydroxylated to yield 7α,12α-dihydroxy-4-cholesten-3-one. In chenodeoxycholic acid synthesis 7α-hydroxy-4-cholesten-3-one is either directly 26-hydroxylated or further reduced to 5β-cholesten-3α,7α-diol which is 26-hydroxylated. Chenodeoxycholic acid is 6β-hydroxylated to α-muricholic acid which is converted to β-muricholic acid.

In a previous study we investigated the influence of cholesterol feeding to germfree rats on some hydroxy-
lases involved in the formation and metabolism of bile acids (2). The 7α-hydroxylation of cholesterol was stimulated 2.5 times, the 12α-hydroxylation of 7α-hydroxy-4-cholesten-3-one was inhibited about 30%, and the 6β-hydroxylation of lithocholic acid was stimulated almost twofold. The 6β-hydroxylase involved in this reaction has the same properties as that active on chenodeoxycholic acid. In the present study we found that cholesterol-fed rats had a threefold greater excretion of fecal bile acids compared to those fed a regular diet. Furthermore, the excretion of β-muricholic acid was increased more than that of cholic acid. These results fit very well with the above mentioned in vitro data, i.e., cholesterol feeding stimulates 7α-hydroxylation of cholesterol and 6β-hydroxylation of chenodeoxycholic acid, whereas 12α-hydroxylation of 7α-hydroxy-4-cholesten-3-one is inhibited.

Previous investigations have given evidence for a certain compartmentation of cholesterol in rat liver (25–27). Cholic acid seems to be formed from newly synthesized cholesterol to a greater extent than chenodeoxycholic acid. Our results are in agreement with such an assumption. The synthesis of chenodeoxycholic acid was stimulated more than that of cholic acid when the input of exogenous cholesterol to the liver was increased and the endogenous formation of cholesterol was depressed.

In conclusion, the present investigation has shown that germfree rats have compensatory mechanisms that are activated when the animals are given increased amounts of cholesterol, i.e., a reduced HMG CoA reductase activity in vitro and an increased formation of bile acids in vivo. Previous reports have shown that germfree rats accumulate more tissue cholesterol than conventional rats (1, 2, 7). Whether this difference between conventional and germfree rats depends on quantitatively more sufficient compensatory mechanisms in conventional rats or may be ascribed to a more efficient absorption of cholesterol from the intestine in germfree rats (3) cannot be decided from the present investigation.

The skillful technical assistance of Miss Anna Persson and Mrs. Margret Wahlström is gratefully acknowledged. This investigation was supported by a grant from the Swedish Medical Research Council (No. 206-13B).

Manuscript received 3 January 1977 and accepted 28 April 1977.

REFERENCES


<table>
<thead>
<tr>
<th>TABLE 2.</th>
<th>The influence of cholesterol feeding on the fecal excretion of bile acids in germfree rats*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cholic Acid</td>
</tr>
<tr>
<td>Rats</td>
<td>mg/kg body weight/day</td>
</tr>
<tr>
<td>Control rats</td>
<td>3.9 ± 0.2</td>
</tr>
<tr>
<td>Cholesterol fed rats</td>
<td>9.9 ± 1.2</td>
</tr>
</tbody>
</table>

* Values are the means ± SEM of eight fecal pools collected from four rats.
# The weight given was the same in the control and cholesterol-fed groups.
& Student's t test.


