Cholesterol Feeding Prevents Hepatic Accumulation of Bile Acids in Cholic Acid-Fed Farnesoid X Receptor (FXR)-Null Mice: FXR-Independent Suppression of Intestinal Bile Acid Absorption

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ABSTRACT:
Cholic acid (CA) feeding of farnesoid X receptor (Fxr)-null mice results in markedly elevated hepatic bile acid levels and liver injury. In contrast, Fxr-null mice fed cholesterol plus CA (CA+Chol) do not exhibit liver injury, and hepatic bile acid levels and bile acid pool size are reduced 51 and 40%, respectively, compared with CA-treated Fxr-null mice. These decreases were not observed in wild-type mice. Despite a reduced bile acid pool size, hepatic Cyp7a1 mRNA expression was increased in Fxr-null mice fed the CA+Chol diet, and biliary bile acid output was not changed. Analysis of other potential protective mechanisms revealed significant decreases in portal blood bile acid concentrations and a reduced ileal bile acid absorption capacity, as estimated using an in situ loop method. Fecal bile acid excretion was also increased in Fxr-null mice fed the CA+Chol versus CA diet. The decreased ileal bile acid absorption correlated with decreased ileal apical sodium-dependent bile salt transporter (ASBT) protein expression in brush-border membranes. These results suggest a critical role for ileal bile acid absorption in regulation of hepatic bile acid levels in Fxr-null mice fed CA+Chol. Furthermore, experiments with Fxr-null mice suggest that cholesterol feeding can down-regulate ASBT expression through a pathway independent of FXR.

Bile acids are synthesized from cholesterol (Chol) in the liver and play a key role in the intestinal absorption of dietary lipids and fat-soluble vitamins. However, pathophysiological accumulation of bile acids can elicit cytotoxicity, and elevated concentrations are associated with liver injury (Hofmann, 1994). Hepatic bile acid levels are tightly regulated by balancing hepatic uptake, biosynthesis, and efflux (Russell, 2003; Trauner et al., 2005; Pauli-Magnus and Meier, 2006). Hepatic bile acid synthesis and uptake are suppressed, and biliary bile acid excretion is enhanced under conditions of hepatic bile acid accumulation. These functional changes are dependent in part on the hepatic levels of CYP7A1, Na+-dependent taurocholate cotransporting polypeptide, and bile salt export pump (Kullak-Ublick et al., 2004; Eloranta et al., 2006; Suchy and Ananthanarayan, 2006; Norlin and Wikvall, 2007). Hepatic bile acid-activated farnesoid X receptor (FXR) signaling plays a critical role in these functional changes by directly up-regulating bile salt export pump expression (Ananthanarayan et al., 2001) and down-regulating CYP7A1 and Na+-dependent taurocholate cotransporting polypeptide expression (Goodwin et al., 2000; Lu et al., 2000; Denson et al., 2001).

In the body, more than 95% of bile acids are reabsorbed at the distal ileum and are carried back to the liver. As such, ileal bile acid absorption mediated by transporters, such as apical sodium-dependent bile salt transporter (ASBT) (gene name Slc10a2) and organic solute transporter α (OSTα)-OSTβ, is also an important potential factor regulating hepatic bile acid levels (Xu et al., 2000; Dawson et al., 2005; Rao et al., 2008). In some strains of mice, bile acids acting via FXR/small heterodimer partner signaling down-regulate ileal ASBT expression (Chen et al., 2003; Neimark et al., 2004; Li et al., 2005). The ileal uptake of bile acids also plays a critical role in regulating hepatic bile acid content by acting via FXR to induce ileal enterocyte expression of fibroblast growth factor 15 (FGF15). The ileal-derived FGF15 is released into the portal circulation and carried to the liver where it signals to down-regulate CYP7A1 expression (Inagaki et al., 2005). Results confirming a central role for ileal-derived FGF15 in the regulation of hepatic CYP7A1 expression were obtained using the

ABBREVIATIONS: Chol, cholesterol; FXR, farnesoid X receptor; ASBT, apical sodium-dependent bile salt transporter; OSTα, organic solute transporter α; FGF, fibroblast growth factor; CA, cholic acid; TCA, taurocholic acid; TCDCA, taurochenodeoxycholic acid; DCA, deoxycholic acid; TDCA, taurodeoxycholic acid; HPLC, high-performance liquid chromatography; ALT, alanine aminotransferase; ALP, alkaline phosphatase; BBM, brush-border membrane; PCR, polymerase chain reaction; GAPDH, glyceraldehyde-3-phosphate dehydrogenase; LXR, liver X receptor; PXR, pregnane X receptor.
intestine-specific Fxr-null mouse (Kim et al., 2007). Thus, hepatic bile acid levels are coordinately modulated by FXR signaling pathways in both liver and small intestine. Furthermore, signaling via pathways not involving FXR is also likely to contribute to the maintenance of hepatic bile acid levels, although the exact mechanisms remain unclear.

Cholesterol can be directly excreted by the liver into bile or converted into bile acids. Approximately half the biliary and dietary cholesterol is reabsorbed in the proximal small intestine (Altmann et al., 2004) and carried back in chylomicrons to the liver. Intestinal cholesterol absorption is facilitated by forming mixed micelles with bile acids (Woollett et al., 2004, 2006; Hui and Howles, 2005). Thus, the bile acid pool size can affect intestinal cholesterol absorption and hepatic cholesterol catabolism (Ponz de Leon et al., 1981; Dawson et al., 2003). Dietary cholesterol increases the bile acid pool size and fecal bile acid excretion in mice (Tiemann et al., 2004). Thus, it is possible that cholesterol feeding increases hepatic bile acid and cholesterol levels.

Cholic acid (CA) feeding markedly increases hepatic bile acid levels and causes liver injury in Fxr-null mice (Sinal et al., 2000), which exhibit impaired regulation of bile acid homeostasis. Hepatic bile acid concentrations are positively correlated with markers of liver injury in Fxr-null mice fed a CA diet (Miyata et al., 2005). Hepatic cholesterol levels are also elevated in CA-fed Fxr-null mice, raising the possibility that accumulation of hepatic cholesterol contributes to the CA-induced hepatotoxicity in this model. In preliminary studies, the effect of cholesterol coadministration on CA-induced hepatotoxicity was tested in Fxr-null mice. We were surprised to find that the addition of cholesterol to the diet ameliorated the hepatotoxicity induced by CA feeding of the Fxr-null mice. To understand the mechanisms underlying the protection against bile acid-induced toxicity in the cholesterol plus CA-fed Fxr-null mice, the effects of cholesterol coadministration on bile acid synthesis and transport were investigated. The present study reveals a role for cholesterol-mediated suppression of ileal bile acid absorption as an important FXR-independent mechanism for reducing hepatic bile acid content and bile acid-induced toxicity.

Materials and Methods

Materials. CA, taurocholic acid (TCA), chenodeoxycholic acid, lithocholic acid, tauroliothocholic acid, taurochenodeoxycholic acid (TCDDCA), deoxycholic acid (DCA), and taurodeoxycholic acid (TDCA) were purchased from Sigma-Aldrich (St. Louis, MO). β-Muricholic acid, tauro-β-muricholic acid, taurosododeoxycholic acid, ursodeoxycholic acid, and 5β-cholanic acid 3α, 6β-diol [internal standard for high-performance liquid chromatography (HPLC)] assay were purchased from Steraloids (Newport, RI). L-Column ODS (2.1 × 150 mm) was obtained from Chemicals Evaluation and Research Institute, Japan (Tokyo, Japan). Enzyme pak 3α-HSD column was purchased from Jasco (Tokyo, Japan). Monoclonal anti-β-antibody (clone AC-15) was purchased from Sigma-Aldrich.

Animal Treatment and Sample Collection. Fxr-null (Sinal et al., 2000) and wild-type mice were housed under a standard 12-h light (9:00 AM to 9:00 PM)/12-h dark cycle. Before administration of the special diets, mice were fed standard rodent chow (CE-2; CLEA Japan, Inc., Tokyo, Japan) and water ad libitum. CE-2 originally contains 0.1% cholesterol. The experimental diets used for these studies included standard control diet (CE-2) or control diet supplemented with the following: 0.5% (w/w) CA, 1.25% Chol, 0.5% CA + 1.25% Chol (CA+Chol), and 0.5% CA + 0.5% Chol (CA+Chol 0.5%). Age-matched groups of 8- to 9-week-old male mice were used for all the experiments. Bile, blood, and tissue samples were taken at 9:00 AM for biochemical assays after feeding the special diets for 6 days. In the present study, the short period (6 days) of feeding was chosen because we originally thought that cholesterol coadministration would enhance CA-induced hepatotoxicity in Fxr-null mice. Total RNA was prepared from livers and ileum using the ULTRASPEC II RNA isolation system (Biotex Laboratories, Inc., Houston, TX). Bile excretion was monitored in mice anesthetized with ethyl ether. After ligating the common bile duct, bile samples were collected by cannulating the gallbladder using polyethylene tubing (PE-10; internal diameter of 0.28 mm). After a 5-min equilibration period, bile was collected for 30 min. Bile acid pool size was determined as bile acid content of the small intestine, liver, and gallbladder. These tissues were removed and extracted in ethanol as described previously (Schwarz et al., 1998). All of the experiments were performed in accordance with Guidelines for Animal Experiments of Tohoku University.

Plasma Diagnosis Parameters and Plasma, Hepatic, and Biliary Lipid Parameters. Plasma alanine aminotransferase (ALT) and alkaline phosphatase (ALP) activities were measured using commercial kits, Transaminase CII-B-test Wako for ALT and Alkaliphospha B-test Wako for ALP (Wako Pure Chemicals, Osaka, Japan). Plasma, hepatic, and biliary total cholesterol concentrations were measured using the cholesterol E-test Wako (Wako Pure Chemicals). Bile acid pool size and hepatic, biliary, and fecal 3α-hydroxy bile acid concentrations were measured by HPLC as described previously (Kitada et al., 2003; Miyata et al., 2006). The content of β-muricholic acid, tauro-β-muricholic acid, ursodeoxycholic acid, tauroursodeoxycholic acid, CA, TCA, chenodeoxycholic acid, TDCA, DCA, lithocholic acid, and tauro-lithocholic acid was measured.

Ileal Bile Acid Absorption (In Situ Loop Method). The mice were anesthetized with ethyl ether. An ileal loop of approximately 10 cm in length was isolated using ligatures at both ends, and 500 μl of a dosing solution (5 mM TDCA in phosphate buffer saline) was injected into the loop with a syringe. The portal blood was collected once from each mouse at 3 or 10 min after the injection.

Western Blot Analysis. Ileal brush-border membranes (BBMs) were prepared as described previously (Kessler et al., 1978). Ileal segments (5 cm) were opened, and the ileal mucosa was obtained by scraping. The ileal mucosa was suspended in 2 mM Tris-HCl, pH 7.1, buffer containing 50 mM mannitol and 0.1 mM phenylmethanesulfonyl fluoride and was homogenized using a Potter homogenizer. After addition of CaCl2 to a final concentration of 10 mM, the homogenate was incubated on ice for 20 min. The homogenate was centrifuged at 3000g for 15 min, and the supernatant was centrifuged at 27,000g for 30 min. The pellet was suspended in 1 mM Hepes, pH 7.5, buffer containing 100 mM mannitol and 10 μM MgSO4.

Ileal BBMs (15 μg/lane) were subjected to SDS-polyacrylamide gel electrophoresis on 8 or 10% polyacrylamide gels and transferred to nitrocellulose filters. The ileal BBM filters were probed with a polyclonal anti-rat ASBT antibody (Shneider et al., 1995; Wong et al., 1995) or monoclonal β-actin antibody (Sigma-Aldrich). The filters were washed five times with Tween 20 containing phosphate buffer and incubated with phosphatase-conjugated goat anti-rabbit IgG (1:3000 dilution). Immunoreactive bands were detected using ECL (Amersham, UK). These cDNA templates were used for real-time polymerase chain reaction (PCR) using SYBR Green 1 with ABI PRISM 7000 Sequence Detection System (Applied Biosystems, Foster City, CA). Quantification was performed by the comparative ΔΔCt method. The following specific forward and reverse primers were used for real-time quantitative PCR: CYP7A1 sense, 5'-AGCAACTAAACAACCTGCCAGTACTA-3' and antisense, 5'-GGATCATCACAGAAGACTTGC-3'. Plasma alanine aminotransferase (ALT) and alkaline phosphatase (ALP) activities were measured using commercial kits, Transaminase CII-B-test Wako for ALT and Alkaliphospha B-test Wako for ALP (Wako Pure Chemicals, Osaka, Japan). Plasma, hepatic, and biliary total cholesterol concentrations were measured using the cholesterol E-test Wako (Wako Pure Chemicals). Bile acid pool size and hepatic, biliary, and fecal 3α-hydroxy bile acid concentrations were measured by HPLC as described previously (Kitada et al., 2003; Miyata et al., 2006). The content of β-muricholic acid, tauro-β-muricholic acid, ursodeoxycholic acid, tauroursodeoxycholic acid, CA, TCA, chenodeoxycholic acid, TDCA, DCA, lithocholic acid, and tauro-lithocholic acid was measured.

Statistical Analysis. All of the values are expressed as the mean ± S.D. Data were analyzed by unpaired Student's t test or by analysis of variance
followed by Tukey’s multiple comparison test using GraphPad Software Inc. (San Diego, CA) Prism 4 for significant differences between the mean values of each group. Probability values of less than 0.05 were considered to be statistically significant.

**Results**

**Liver Damage Diagnostic Markers and Bile Acid Content in CA and/or Cholesterol-Fed Mice.** Feeding CA resulted in elevated hepatic bile acid levels, and plasma ALT but not ALP activities were slightly increased in wild-type mice fed the CA or CA+Chol diets (Table 1), with levels less than 200 IU/l. However, there was no significant difference between wild-type mice fed the CA and CA+Chol diets with regard to plasma ALT or hepatic bile acid content. In contrast to wild-type mice, the CA-fed Fxr-null mice had markedly elevated plasma ALT and ALP activities (13.5- and 10.0-fold, respectively, relative to the control diet) (Table 1). Plasma ALT and ALP activities were also elevated in Fxr-null mice fed the CA+Chol diet; however, the increases were significantly blunted compared with the CA-fed Fxr-null (20 and 48% of the CA diet levels, respectively). The hepatic bile acid content was also markedly increased in Fxr-null mice fed the CA diet (4.6-fold relative to the control diet) (Table 1). However, as with the liver damage diagnostic markers, feeding CA+Chol diet significantly blunted the increase in hepatic bile acid levels; in the Fxr-null mice fed CA+Chol, hepatic bile acid content was decreased 51% compared with the CA-fed Fxr-null mice. Significant increases in hepatic cholesterol levels were observed in Fxr-null mice fed the Chol, CA, and CA+Chol diets and in wild-type mice fed the CA+Chol diet (Table 1). In contrast to liver, plasma cholesterol levels were significantly increased only in Fxr-null mice fed the CA+Chol diet. The effect of cholesterol on CA-induced toxicity and hepatic bile acid content was further examined in Fxr-null mice fed diets containing CA and increasing amounts (0.5, 0.5, and 1.25%) of cholesterol. Feeding increasing amounts of dietary cholesterol plus CA to Fxr-null mice reversed the elevation of hepatic bile acid content and plasma ALT and ALP activities in a dose-dependent manner (Fig. 1, A and B). An inverse relationship was found between hepatic content of bile acids and cholesterol (Fig. 1C).

**Influence of Cholesterol on Bile Acid Pool Size.** To determine whether the decreased hepatic bile acid levels in Fxr-null mice fed the CA+Chol diet is reflected in whole-body bile acid levels, bile acid pool sizes were also measured (Table 2). There were no significant differences in bile acid pool size and composition between wild-type mice fed the CA and CA+Chol diets. Despite significantly higher hepatic levels of bile acids in the CA-fed Fxr-null mice compared with CA-fed wild-type mice, the total bile acid pool tended to be lower in the Fxr-null mice. Thus, ratio of the hepatic bile acid content to total bile acid pool size in Fxr-null mice fed a CA diet was 6.5 times higher than that in wild-type mice. However, consistent with changes in hepatic bile acid levels, the bile acid pool size in CA+Chol diet-fed Fxr-null mice was decreased 40% compared with CA-fed Fxr-null mice. Analysis of the bile acid pool’s composition revealed a significant decrease in total CA (TCA + CA) contents in Fxr-null mice fed the CA+Chol diet versus CA diet (Table 2). Significant decreases in total DCA (TDCA + DCA) contents were observed in Fxr-null mice compared with wild-type mice.

**Hepatic Bile Acid Synthesis and Secretion in Fxr-Null Mice Fed CA and/or Cholesterol.** Cholesterol feeding may protect the liver from bile acid accumulation by inducing hepatic bile acid secretion. Initially, the hepatic expression of CYP7A1 was examined in Fxr-null and wild-type mice fed the control, CA, and CA+Chol diets. CYP7A1 mRNA levels were significantly lower in Fxr-null and wild-type mice fed the CA diet compared with the control diet (Fig. 2), whereas CYP7A1 mRNA expression was significantly higher in those mice fed the CA+Chol diet compared with the CA diet. To determine the influence of cholesterol coadministration on biliary bile acid excretion in Fxr-null mice fed the CA diet, biliary bile acid output rates were determined. No differences in biliary bile acid

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**TABLE 1**

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<th>Wild-Type</th>
<th>Fxr-Null</th>
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<tr>
<td></td>
<td>Cont</td>
<td>Chol</td>
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<tr>
<td>Liver bile acid (nmol/g liver)</td>
<td>157 ± 42</td>
<td>72 ± 68</td>
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<tr>
<td>Liver cholesterol (mg/g liver)</td>
<td>2.72 ± 0.32</td>
<td>2.66 ± 0.46</td>
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<tr>
<td>Plasma cholesterol (mg/dl)</td>
<td>75 ± 5</td>
<td>57 ± 6</td>
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<tr>
<td>ALT (IU/l)</td>
<td>8 ± 1</td>
<td>12 ± 2</td>
</tr>
<tr>
<td>ALP (IU/l)</td>
<td>29 ± 4</td>
<td>30 ± 5</td>
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<sup>a</sup>p < 0.05 versus control group.

<sup>b</sup>p < 0.05 versus CA group.
FIG. 2. Hepatic levels of CYP7A1 mRNA. Hepatic CYP7A1 mRNA levels were measured by real-time quantitative PCR. Hepatic RNAs were prepared from Fxr-null and wild-type mice fed a control diet (Cont) or diet supplemented with 0.5% CA or 0.5% CA and 1.25% Chol (CA + Chol) for 6 days. The mRNA expression levels were normalized to GAPDH mRNA. Ct values for CYP7A1 and GAPDH of wild-type mice fed control diet were 29.1 and 22.0, respectively. Data are shown as the mean ± S.D. (n = 4). The data are representative of two independent experiments. *, p < 0.05 and ***, p < 0.001 versus control diet group. #, p < 0.05 versus CA diet group.

FIG. 3. Changes in biliary bile acid excretion in Fxr-null mice. Fxr-null mice were fed a control diet (Cont) or diet supplemented with 0.5% CA or 0.5% CA and 1.25% Chol (CA + Chol) for 6 days. Bile was collected for 30 min by bile duct cannulation. Data are shown as the mean ± S.D. (n = 5). The data are representative of two independent experiments.

FIG. 4. Portal blood bile acid levels. Fxr-null and wild-type mice were fed a control diet (Cont) or diet supplemented with 1.25% Chol, 0.5% CA, or 0.5% CA and 1.25% Chol (CA + Chol) for 6 days. Portal blood was collected from mice anesthetized with ethyl ether. Bile acid concentration was measured by HPLC as described under Materials and Methods. Data are shown as the mean ± S.D. (n = 3). The data are representative of two independent experiments. *, p < 0.05 and **, p < 0.01 versus control diet group. #, p < 0.05 versus CA diet group.
significant differences in the concentration were observed between CA diet and CA+Chol diet. These results suggest that cholesterol coadministration decreases ileal bile acid absorption capacity in Fxr-null mice fed the CA diet but not the wild-type mice.

Fecal bile acid excretions in Fxr-null mice fed the control, CA, and CA+Chol diets were $9.4 \pm 1.1$, $14.2 \pm 3.2$, and $55.7 \pm 15.5$ μmol/day/100 g b.wt. (mean ± S.D.; n = 5), respectively. The fecal bile acid excretion was significantly increased in Fxr-null mice fed CA and CA+Chol diets compared with Fxr-null mice fed the control diet. Furthermore, concomitant with decreases in ileal bile acid absorption, fecal bile acid excretion was significantly increased in Fxr-null mice fed the CA+Chol versus CA diet. In wild-type mice, no significant differences in fecal bile acid excretion were observed between CA diet (52.1 ± 4.5 μmol/day/100 g b.wt.) and CA+Chol diet (52.1 ± 4.5 μmol/day/100 g b.wt.).

Ileal ASBT Protein and mRNA Levels. To identify the mechanisms responsible for reduced ileal bile acid absorption in Fxr-null mice fed the CA+Chol diet, the expression of ASBT protein in ileal BBMs was analyzed by Western blot analysis. Proteins recognized by Asbt antibody were higher in ileal BBMs than those in duodenum BBMs from wild-type mice fed CA diet (data not shown). Marked decreases in the contents were found in both wild-type and Fxr-null mice fed the CA+Chol diet compared with those mice fed the CA diet (Fig. 6A). Ileal ASBT mRNA levels were not significantly lower in Fxr-null and wild-type mice fed CA+Chol diet compared with those mice fed CA diet (Fig. 6B), although marked differences in the protein contents were observed. Similar levels of ileal bile acid binding protein and OSTα mRNAs were observed between Fxr-null mice fed the CA diet and CA+Chol diet (data not shown).

Discussion

The present study revealed that cholesterol coadministration decreases bile acid pool size and hepatic bile acid concentrations in CA-fed Fxr-null mice. Among the potential mechanisms responsible for the effects of cholesterol coadministration are decreased hepatic bile acid synthesis and decreased intestinal absorption. However, mRNA expression for CYP7A1, the rate-limiting enzyme for hepatic bile acid synthesis was significantly increased in Fxr-null mice fed the CA+Chol diet compared with the CA diet. In contrast, several lines of evidence suggest that ileal bile acid absorption is decreased in Fxr-null mice fed the CA+Chol diet. This includes the findings that the portal blood bile acid concentration was significantly decreased, ileal bile acid absorption was significantly reduced as measured using an in situ loop model, and fecal bile acid excretion was increased. Thus, ileal bile acid absorption is probably responsible in part for the reduced bile acid hepatic accumulation and bile acid pool size in CA+Chol-fed Fxr-null mice.

Changes in the ileal BBM content of ASBT protein correlated with ileal bile acid absorption rates in Fxr-null but not wild-type mice fed the CA and CA+Chol diets. ASBT-mediated uptake across the BBM is thought to be one of the rate-limiting steps in bile acid transport from the gut lumen into the portal circulation. As such, in Fxr-null mice, the reduced ileal ASBT protein expression probably accounts for the decreased ileal bile acid absorption capacity under the condi-
tions of bile acid and cholesterol feeding, although other mechanisms for the reduction of ileal bile acid absorption cannot be excluded. Previous studies have shown that the bile acid pool size is decreased in Asbt-null mice or ASBT inhibitor-treated rabbits, despite increased CYP7A1 expression (Dawson et al., 2003; Li et al., 2004). In contrast, cholesterol-fed rabbits exhibit increased ileal ASBT expression and an increased bile acid pool size, despite reduced cholesterol 7α-hydroxylase activity (Xu et al., 2000). These reports support the hypothesis that ileal ASBT protein expression is at least partially responsible for controlling the bile acid pool size and hepatic bile acid levels in Fxr-null mice fed CA+Chol.

Previous studies have reported that feeding a diet containing 2% cholesterol to C57BL/6J mice for 14 days decreased ileal expression of ASBT protein and mRNA (Thomas et al., 2006). The present results found a similar decrease in ASBT protein expression in Fxr-null and wild-type mice fed cholesterol in addition to CA. However, the decrease in ileal ASBT mRNA expression in Fxr-null and wild-type mice fed the CA+Chol diet was not significant in the present study. The differences in regulation of ASBT mRNA expression between the two studies may reflect the inclusion of CA and different amounts of cholesterol (0.02 versus 0.1% in the control diet and 2 versus 1.25% in the cholesterol supplement diet) and the length of feeding (14 versus 6 days). Although long-term cholesterol feeding might be necessary for the cholesterol-mediated regulation of ileal ASBT mRNA level in mice, the present studies were limited to 6 days because of increased toxicity after this time. Marked decrease (more than 30%) in body weight and severe physical debilitation were observed in some of Fxr-null mice fed CA diet for 10 days. It should be noted that both studies found that the decreases in ileal ASBT protein expression was greater than the change in ASBT mRNA expression. These results raise the possibility that cholesterol can down-regulate ASBT protein expression in the ileal BBM by post-translational mechanisms such as protein stability or membrane translocation. Post-translational regulation of ASBT has previously been reported. For example, it has been shown in tissue culture cells that interleukin-1β can down-regulate ASBT expression by inducing the ubiquitinylating and proteasomal degradation of ASBT protein (Xia et al., 2004). Very recently, it was shown that ASBT protein is localized in cholesterol-containing rafts, and modulation of the cholesterol content regulated ASBT activity. However, in those studies, depletion of membrane cholesterol by using methyl-β-cyclodextrin inhibited ASBT activity in tissue culture cells (Annaba et al., 2008). Although our studies indicate that FXR is not required for this cholesterol regulation of ASBT protein expression, the underlying mechanisms responsible remain to be identified. It has been reported that human ASBT expression is directly down-regulated by 25-hydroxycholesterol (Alrefai et al., 2005). The suppressive effect of cholesterol and 25-hydroxycholesterol on ASBT expression is mediated through sterol regulatory element binding protein 2 and hepatic nuclear factor 1α in Caco-2 cells (Thomas et al., 2006). ASBT expression is probably down-regulated at least by two distinct mechanisms: cholesterol signaling (sterol regulatory element binding protein) and bile acid signaling (FXR/small heterodimer partner). Cholesterol-mediated signaling seems to play a crucial role in the down-regulation of ileal ASBT expression by the conditions of lacking negative feedback regulation by FXR signaling such as found in the Fxr-null mice. The cholesterol-mediated suppression of ileal ASBT expression might be a second defense system against hepatic bile acid accumulation.

Cholesterol metabolites and intermediates in the bile acid biosynthetic pathway can activate liver X receptor (LXR) and pregnane X receptor (PXR) (Goodwin et al., 2003; Sonoda et al., 2005). Feeding the 1.25% cholesterol-containing diet might lead to an accumulation of these intermediates, which activate LXR and PXR. Under conditions of absence of FXR, activated LXR and PXR might suppress hepatic bile acid accumulation to protect liver against CA-induced injury (Guo et al., 2003; Teng and Piquette-Miller, 2007).

No significant differences in bile acid pool size were observed between Fxr-null and wild-type mice fed a CA diet, whereas marked differences in hepatic bile acid content were found. These results raise a possibility that under the CA feeding condition, FXR signaling plays a crucial role in the suppression of accumulating hepatic bile acid content but not that of bile acid pool size. On the other hand, cholesterol-mediated signaling is probably involved in the suppression of accumulating bile acid pool size and hepatic bile acid content under the high bile acid condition of lacking FXR.

In the present study, we showed that cholesterol feeding prevents hepatic bile acid accumulation in CA-fed Fxr-null mice via down-regulation of ileal bile acid absorption. Furthermore, using Fxr-null mice cotreated with cholesterol and CA, we showed a crucial role of ileal bile acid absorption in regulation of hepatic bile acid levels. Because CA-fed Fxr-null mice markedly increase hepatic bile acid levels, the mice seem to be a good model to identify bile acid regulatory mechanisms independent of FXR signaling. The cholesterol-mediated negative regulation of ileal bile acid absorption may be involved in the maintenance of not only bile acid but also cholesterol homeostasis. Further studies are necessary to identify the mechanism for the suppression of ileal bile acid absorption through cholesterol signaling.

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References


