Acceleration of Biliary Cholesterol Secretion Restores Glycemic Control and Alleviates Hypertriglyceridemia in Obese db/db Mice

Kai Su,* Nadezhda S. Sabeva,* Yuhuan Wang, Xiaoxi Liu, Joshua D. Lester, Jingjing Liu, Shuang Liang, Gregory A. Graf

Objective—Recent studies support a role for cholesterol in the development of obesity and nonalcoholic fatty liver disease. Mice lacking the ABCG5 ABCG8 (G5G8) sterol transporter have reduced biliary cholesterol secretion and are more susceptible to steatosis, hepatic insulin resistance, and loss of glycemic control when challenged with a high-fat diet. We hypothesized that accelerating G5G8-mediated biliary cholesterol secretion would correct these phenotypes in obese mice.

Approach and Results—Obese (db/db) male and their lean littermates were administered a cocktail of control adenovirus or adenoviral vectors encoding ABCG5 and ABCG8 (AdG5G8). Three days after viral administration, measures of lipid and glucose homeostasis were determined, and tissues were collected for biochemical analyses. AdG5G8 increased biliary cholesterol and fecal sterol elimination. Fasting glucose and triglycerides declined, and glucose tolerance improved in obese mice expressing G5G8 compared with mice receiving control adenovirus. These changes were associated with a reduction in phosphorylated eukaryotic initiation factor 2α and c-Jun N-terminal kinase in liver, suggesting alleviation of endoplasmic reticulum stress. Phosphorylated insulin receptor and protein kinase B were increased, indicating restored hepatic insulin signaling. However, there was no reduction in hepatic triglycerides after the 3-day treatment period.

Conclusions—Accelerating biliary cholesterol secretion restores glycemic control and reduces plasma triglycerides in obese db/db mice. (Arterioscler Thromb Vasc Biol. 2014;34:26-33.)

Key Words: bile ■ cholesterol ■ insulin resistance ■ liver steatosis ■ obesity

The causal role of cholesterol in the development of cardiovascular disease is well-established, but an emerging body of literature indicates that cholesterol may also contribute to the development of obesity and the severity of nonalcoholic fatty liver disease (NAFLD). Dietary cholesterol and fat act synergistically to promote obesity and the development of NAFLD in C57BL/6j mice. Similarly, the addition of cholesterol to a high-fat, high-sucrose diet also exacerbates the development of insulin resistance and steatosis in low-density lipoprotein receptor (LDLR)–deficient mice. In a mouse model of Alström syndrome, hepatic cholesterol accumulation is associated with disruptions in both cholesterol uptake and elimination pathways and correlates with the severity of liver phenotypes. Conversely, the inhibition of cholesterol absorption with ezetimibe (EZ) opposes the development of obesity, insulin resistance, and steatosis in both rats and mice. Mouse lacking the target of EZ, Niemann-Pick C1–like 1 protein, are protected from NAFLD and the development of obesity and insulin resistance. However, the addition of cholesterol to the diet reverses this phenotype, suggesting that the presence of cholesterol in the intestine modulates metabolism independently of its absorption. In the LDLR model challenged with a high-cholesterol diabetogenic diet, EZ reduced hepatic steatosis but not other obesity phenotypes such as adipose tissue inflammation. EZ was shown to produce a modest, but significant, reduction in hepatic fat and liver enzymes in a Japanese population of patients with NAFLD. In addition, a recent clinical trial suggests that EZ may improve measures of insulin resistance in diabetic insulin-resistant subjects.

The ABCG5 ABCG8 (G5G8) heterodimer functions as a xenobiotic transporter that opposes the absorption of phytosterols and their accumulation in plasma and tissues in both mice and humans. G5G8 also promotes cholesterol secretion...
Nonstandard Abbreviations and Acronyms

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<th>Abbreviation</th>
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<tr>
<td>AdG5G8</td>
<td>adenoviral vectors encoding G5G8</td>
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<td>Apo B</td>
<td>apolipoprotein B</td>
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<tr>
<td>ATF</td>
<td>activating transcription factor</td>
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<td>eiF2α</td>
<td>eukaryotic initiation factor 2α</td>
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<td>ER</td>
<td>endoplasmic reticulum</td>
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<td>EZ</td>
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<td>G5G8</td>
<td>ABCG5 ABCG8 sterol transporter</td>
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<td>GRP</td>
<td>glucose-regulated protein</td>
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<td>LDLR</td>
<td>low-density lipoprotein receptor</td>
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<td>NAFLD</td>
<td>nonalcoholic fatty liver disease</td>
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<td>PERK</td>
<td>pancreatic eiF2α kinase</td>
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<td>SREBP</td>
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<td>Trb3</td>
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expression of lipogenic genes, increased Akt phosphorylation, and reduced eiF2α signaling, suggesting that G5G8-mediated biliary cholesterol secretion alleviates ER stress and restores insulin signaling. However, steatosis was not reduced in this short-term experiment. Additional studies in which stable expression of G5G8 is achieved will be required to determine whether accelerated biliary cholesterol secretion can improve hepatic steatosis in models of obesity and insulin resistance.

Materials and Methods

Materials and Methods are available in the online-only Supplement.

Results

Biliary Cholesterol Elimination

We have previously used adenoviral vectors to transiently increase G5G8 and biliary cholesterol.31 Before initiating studies in db/db mice, we conducted a pilot study to confirm that AdG5G8 could increase fecal sterol output during the planned treatment period. Fecal neutral sterols increase within 2 days and remain elevated for ≤6 days after AdG5G8 delivery (Figure I in the online-only Data Supplement). Obese (db/db) mice and their lean littermates were injected with a cocktail of adenoviral particles encoding ABCG8 and an empty vector (control) or both ABCG5 and ABCG8 (AdG5G8), and tissues were dissected 3 days after viral delivery. G5 and G8 are obligate heterodimers that require coexpression for complex formation, trafficking to the cell surface, and biliary cholesterol secretion. Both G5 and G8 contain N-linked glycans and heterodimer formation, and trafficking to the cell surface can be monitored by the appearance of the mature, post-Golgi forms of both proteins by SDS-PAGE and immunoblot analysis.32 The immature form of recombinant G8 is observed in all mice, but the mature form is only observed in mice receiving the G5 adenovirus (Figure 1A). Similarly, the mature form of recombinant G5 is only observed in AdG5G8-injected mice that express functional G5G8. AdG5G8 did not increase intestinal levels of the G5G8 transporter, nor did viral cocktails differentially affect liver enzymes or the expression of inflammatory genes in liver (Figure II in the online-only Data Supplement).

We next measured biliary cholesterol and fecal neutral sterols as indirect measures of G5G8 function. AdG5G8 increased biliary cholesterol concentrations in both lean and obese mice by 5.2-fold and 5.7-fold, respectively (Figure 1B). We also blotted for the class B, type 1 scavenger receptor because this protein can mediate G5G8-independent biliary cholesterol secretion.30 Class B, type 1 scavenger receptor is reduced in db/db mice compared with lean controls but is not elevated in either lean or db/db mice after AdG5G8 treatment (Figure 1A). The overall ANOVA indicated a significant increase in fecal neutral sterols in AdG5G8-injected mice, regardless of the genotype (P<0.01). Post hoc analysis indicated 4.4-fold and 2.9-fold increases in lean and obese mice, respectively. Although levels of G5G8 protein are lower in db/db mice compared with lean controls, biliary cholesterol and fecal neutral sterol levels increase to a similar extent.
The loss of glycemic control and hepatic phenotypes in obese G5G8-deficient mice were associated with increased activation of some components of the unfolded protein response (UPR), in particular phosphorylation of eIF2α.22 Therefore, we determined whether AdG5G8 reduced phospho-eIF2α and suppressed other components of the UPR in livers of db/db mice. Immunoblot analysis demonstrated a reduction in phospho-eIF2α but not in total eIF2α in AdG5G8-treated obese mice compared with control virus (Figure 3A and 3B). The reduction in phospho-eIF2α was associated with less ATF4 mRNA expression and its downstream target, Trb3 (Figure 3C). Trb3 is a negative regulator of insulin-mediated Akt phosphorylation in liver.13 The decrease in Trb3 was associated with an increase in phospho-Akt but not total Akt, suggesting that alleviation of ATF4-Trb3 signaling plays a role in the restoration of insulin signaling in the livers of AdG5G8-treated db/db mice.

To further investigate UPR signaling, we blotted for total and phosphorylated c-Jun N-terminal kinase and pancreatic eIF2α kinase (PERK). Consistent with reduced ER stress, phospho-c-Jun N-terminal kinase declined after AdG5G8 administration. However, we did not observe elevations in phospho-PERK. In addition, other components of the UPR are largely unaffected in db/db mice treated with AdG5G8 compared with control virus. This includes expression of the ATF6 target genes glucose-regulated protein (GRP) 78, GRP94, CCAAT-enhancer-binding proteins (C/EBP)-homologous protein, and X box–binding protein 1. However, we did detect a modest but significant reduction in spliced X box–binding protein 1, consistent with reduced inositol-requiring enzyme 1 activation. Collectively, these data support a role for accelerated biliary cholesterol secretion in the reduction of eIF2α signaling, but the kinase and initiating events remain to be resolved.

**Plasma and Hepatic Lipids**

We broadly assessed changes in genes related to insulin signaling in db/db mice using pooled RNA from animals infected with either control virus or AdG5G8 and analyzed by an insulin signaling pathway polymerase chain reaction array (Figure III in the online-only Data Supplement). The majority of genes assayed were unaltered, but key genes in both the lipogenic and gluconeogenic pathways were suppressed, including the lipogenic transcription factor, sterol regulatory–binding protein (SREBP). We confirmed suppression of mRNAs for SREBP1 and its target genes acetyl coenzyme A carboxylase and fatty acid synthase by reverse-transcriptase polymerase chain reaction in individual mice (Figure 4A). Consistent with the reduction in mRNA, full-length SREBP1 protein was lower after AdG5G8 delivery (Figure 4B and 4C). There was also a tendency toward lower levels of cleaved SREBP in nuclear extracts. However, there was no difference in hepatic TG levels 72 hours after AdG5G8 treatment in either lean or db/db mice (Figure 4D). We next measured plasma TGs and TG secretion rates (Figure 4E and 4F). TGs were normalized in db/db mice, and the TG secretion rate was reduced (542±31 versus 428±23 mg/dL per hour; P<0.01) after AdG5G8 administration in db/db mice. However, levels of apolipoprotein B (ApoB) and microsomal TG transfer protein mRNAs were unchanged (not shown).
Despite elevations in biliary and fecal sterols, plasma cholesterol was paradoxically increased after AdG5G8 administration in both lean and obese mice (Figure 5A). Fast protein liquid chromatography fractionation of pooled serum revealed that the increase in cholesterol was caused by the accumulation of large particles. High-density lipoprotein levels, which are characteristically elevated in db/db mice, declined in both genotypes. A significant fraction of biliary cholesterol is reabsorbed in the small intestine. Therefore, we tested the hypothesis that the unexpected increase in plasma cholesterol after AdG5G8 administration could be averted by coadministration of the cholesterol absorption inhibitor, EZ. In a separate cohort of lean strain-matched mice, we pretreated mice with EZ before administration of control or AdG5G8 virus. As in lean and db/db littermates, AdG5G8 increased plasma cholesterol and promoted the accumulation of large cholesterol ester–enriched particles but not in mice in which intestinal absorption was inhibited by pretreatment with EZ (Figure 5D). Immunoblot analysis of peak fractions revealed that these particles are enriched in both ApoB and ApoE (Figure 5E). Although there is a tendency toward the accumulation of ApoE in whole serum, this difference did not reach statistical significance, and ApoE mRNA was not increased in either liver or intestine (Figure IV in the online-only Data Supplement).

Hepatic cholesterol also increased in db/db AdG5G8-treated mice, but unlike plasma cholesterol this was not observed in their lean littermates (Figure 6A). Next, we measured the expression of genes involved in cholesterol synthesis and uptake. Irrespective of viral administration, mRNA levels of SREBP2, 3-hydroxy-3-methylglutaryl-coenzyme A reductase, and 3-hydroxy-3-methylglutaryl-coenzyme A synthase 1 were reduced in db/db mice compared with lean controls. Conversely, very-LDLR mRNA levels, which are normally very low in liver, are significantly elevated. In lean mice, AdG5G8 resulted in increased expression of genes required for cholesterol synthesis, suggesting that hepatic cholesterol synthesis increased to maintain hepatic sterol levels in response to accelerated biliary secretion. This effect was not observed in db/db mice presumably because of the accumulation of cholesterol in liver. Protein levels of 3-hydroxy-3-methylglutaryl-coenzyme A reductase and LDLR were determined in liver lysates from db/db mice (Figure 6). Although there was a trend for increases, neither reached statistical significance.

### Discussion

The major findings of the present study are that increased G5G8-mediated biliary cholesterol secretion restores glycemic control, improves hepatic insulin signaling, and reduces plasma triglycerides in obese and insulin-resistant db/db mice. These phenotypic differences were associated with reduced markers of ER stress and increased measures of insulin signaling in liver. The abundance of mRNAs for lipogenic genes was reduced, but AdG5G8 failed to lower hepatic lipid content during the 3-day treatment period. Whether sustained expression...
of G5G8 and accelerated biliary cholesterol secretion during a longer period would promote clearance of hepatic TGs will require alternative approaches to transient expression by adenoviral gene delivery.

G5G8 and the UPR
This study is the converse of our previous work showing that the absence of G5G8 exacerbates the development of insulin resistance, steatosis, and inflammation in diet-induced obesity.22 In the previous study, the development of hepatic insulin resistance was associated with an increase in eiF2α signaling and reduced phospho-Akt. Consistent with this pathway playing a causative role in hepatic insulin resistance in G5G8-deficient mice, the overexpression of G5G8 in db/db mice reduced eiF2α signaling and increased phospho-Akt. An interesting feature of UPR activation in G5G8 deficiency and its alleviation by AdG5G8 administration in obese mice; the effect of GRP78 on the PERK arm of the UPR. The prevailing model for activation of the UPR is the release of inositol-requiring enzyme 1 (IRE1), ATF6, and PERK from GRP78 by the accumulation of misfolded and unfolded proteins. Although there is some evidence for selective activation of the UPR but is rather an alternate mechanism for activating eiF2α. In addition, a recent report indicates that PERK and inositol-requiring enzyme 1 are responsive to changes in membrane lipid composition, independently of changes in protein folding in the ER.23 Whether membrane cholesterol content similarly affects UPR signaling is not known. The question of how G5G8 influences UPR signaling remains unresolved in the present study because we have yet to mechanistically link the absence of G5G8 to activation of a specific eiF2α kinase or other element of the UPR.

Figure 3. Adenoviral vectors encoding G5G8 (AdG5G8) reduces eukaryotic initiation factor 2α (eiF2α) signaling in db/db mice. Obese (db/db) mice were administered control and AdG5G8 vectors. A, Total and phosphorylated (P-) eiF2α, Akt, c-Jun N-terminal kinase (JNK), and pancreatic eiF2α kinase (PERK) were assessed in hepatic lysates by SDS-PAGE and immunoblotting. The activating transcription factor (ATF) 6 target genes glucose-regulated protein (GRP) 78 and GRP94 were also assessed. β-actin was used as a loading control. B, The ratios of phosphorylated to total eiF2α, Akt, and JNK were determined by densitometry. C, Reverse-transcriptase polymerase chain reaction was used to measure downstream signaling for eiF2α (ATF4, tribbles 3 [Trb3]), ATF6 (GRP78, X box–binding protein 1 [XBP-1]), and inositol-requiring enzyme 1 (spliced sXbp1). Data are mean±SEM (n=4). *P<0.05, **P<0.01, ***P<0.001. CHOP indicates C/EBP-homologous protein.

Leptin and G5G8
In both ob/ob and db/db mice, G5G8 protein levels are posttranscriptionally reduced and can be increased by caloric restriction or the administration of molecular chaperones. This suggests that reductions in G5G8 are independent of leptin signaling and that ER stress may directly affect G5G8
ER.37 Conversely, neither diabetes mellitus nor obesity alone is dependent manner.38

Insulin signaling through liver-specific deletion of insulin receptor increases G5G8 mRNA in a forkhead box O1A–element–binding protein (SREBP) 1 were analyzed by immunoblotting in whole cell lysates and nuclear extracts, respectively. C, Densitometry of SREBP immunoblots. Signal intensities are normalized to calnexin (CNX) and expressed as percent of the control mean. D and E, Plasma and hepatic TGs were determined by enzymatic colorimetric assay. F, TG secretion rates were determined after injection of Triton WR 1339. Data are mean±SEM (n=3–4). *P<0.05, **P<0.01, ***P<0.001.

Figure 4. Adenoviral vectors encoding G5G8 (AdG5G8) reduces lipogenic gene expression and lowers plasma triglycerides (TGs). Obese (db/db) male mice and their lean littermates were administered control or AdG5G8 virus. A, Total RNA was extracted from liver 72 hours after viral administration and was analyzed by reverse-transcriptase polymerase chain reaction for expression of lipogenic genes. B, Full-length and processed sterol regulatory element–binding protein (SREBP) 1 were analyzed by immunoblotting for apolipoprotein B (ApoB). HDL indicates high-density lipoprotein; and LDL, low-density lipoprotein.

Perhaps this is not surprising given the dependen
cency of G5G8 formation on lectin chaperones within the ER.37 Conversely, neither diabetes mellitus nor obesity alone is sufficient to reduce hepatic G5G8.30 We recently evaluated another model of obesity and insulin resistance for abundance of G5G5 at the protein level: LDLR-deficient mice maintained on a high-fat, high-cholesterol, Western-type diet for 16 weeks. In this model, G5 protein levels are increased because of the activation of liver X receptor by high-cholesterol diet

abundance.30 Perhaps this is not surprising given the dependence of G5G8 formation on lectin chaperones within the ER.37 Conversely, neither diabetes mellitus nor obesity alone is sufficient to reduce hepatic G5G8.30 We recently evaluated another model of obesity and insulin resistance for abundance of G5G5 at the protein level: LDLR-deficient mice maintained on a high-fat, high-cholesterol, Western-type diet for 16 weeks. In this model, G5 protein levels are increased because of the activation of liver X receptor by high-cholesterol diet

Figure 5. Adenoviral vectors encoding G5G8 (AdG5G8)-dependent increase in plasma cholesterol is blocked by ezetimibe. A and B, Lean and obese db/db mice were administered control and AdG5G8 vectors. C and E, C57Bl/6J mice were administered the control vector or AdG5G8 in the absence or presence of ezetimibe (AdG5G8+ezetimibe [EZ]). Cholesterol in total (A and C) and fast protein liquid chromatography (FPLC)-fractionated (B and D) serum was determined by enzymatic colorimetric assay. E, FPLC fraction of 8 samples (peak cholesterol) from 3 mice in each group was pooled and analyzed by immunoblotting for apolipoprotein B (ApoB). HDL indicates high-density lipoprotein; and LDL, low-density lipoprotein.

EZ to block this effect of AdG5G8 indicates that this is most likely because of intestinal reabsorption of cholesterol from enriched bile. An enterohepatic pool of cholesterol has been described and is thought to expand during the development of obesity in mice.39 The apparent expansion of this pool of cholesterol resulted in perturbations of plasma and hepatic cholesterol homeostasis that are difficult to unravel and are beyond the scope of the present study. However, this observation highlights the fact that accelerating biliary cholesterol secretion is ineffective in reducing plasma cholesterol unless there is a concomitant increase in intestinal G5G8 or other secretory mechanisms to oppose reabsorption. Similar observations were made in transgenic mice. A liver-specific G5G8 transgene was ineffective in reducing plasma cholesterol or atherosclerosis in the absence of EZ, whereas a human G5G8 transgene under the control of the endogenous promoter that mitigates the effectiveness of cholesterol elimination in response to liver X receptor agonists, there is a G5G8-independent component that is yet to be elucidated.43 Although this pathway can compensate for disruptions in biliary cholesterol elimination, it is not clear

G5G8 and Cholesterol Homeostasis

The increase in plasma cholesterol levels after AdG5G8 administration in db/db mice was unexpected. The ability of
how hepatic and intestinal pathways cooperate to maintain cholesterol homeostasis. In this and previous studies in which hepatic cholesterol secretion is significantly elevated, transintestinal cholesterol elimination is insufficient to prevent the reabsorption and accumulation of cholesterol in plasma.

**Limitations**

The primary limitation of the present study is the use of adenoviral vectors to test the effect of increased G5G8-mediated biliary cholesterol elimination. These vectors dramatically increase protein expression that peaks between 48 and 72 hours after administration and then declines at a rate that is largely dependent on the half-life of the recombinant protein. Alternatively, there may have been a robust, transient increase in hepatic synthesis followed by repression as cholesterol accumulates in liver. Given the dynamic nature of adenoviral-mediated gene expression, mice are unlikely to achieve steady state. Consequently, studies to evaluate the efficacy of accelerated biliary cholesterol elimination on hepatic steatosis will require approaches that result in sustained increases in G5G8 expression. Such approaches will also facilitate examination of other features of NAFLD such as inflammation and apoptosis.

**Acknowledgments**

We thank Dr Victoria King (University of Kentucky) for liver samples from low-density lipoprotein receptor–deficient mice.

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**Disclosures**

None.

**References**

G5G8 Restores Glycemic Control in Obese db/db Mice

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Significance

This study demonstrates for the first time that active elimination of cholesterol through the biliary compartment can reduce unfolded protein response signaling, restore glycemic control, and reduce plasma triglycerides in a mouse model of obesity and insulin resistance that is characterized by elevated levels of endoplasmic reticulum stress. These findings add to a growing body of literature that supports a causal role for cholesterol in the development of obesity-related liver phenotypes. It also suggests that therapeutic approaches to actively reduce hepatic cholesterol in the setting of obesity and insulin resistance may provide benefit in the treatment of insulin resistance and nonalcoholic fatty liver disease.
Acceleration of Biliary Cholesterol Secretion Restores Glycemic Control and Alleviates Hypertriglyceridemia in Obese db/db Mice

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Fig SI. Nine C57 mice were group housed in clean cages (3/cage) and feces collected for 48 hr prior to viral delivery (Day 0). AdG5G8 was administered on Day 0 and feces collected on day 2, 4, 6, 10 and 14. Feces from were dried, lipids extracted and analyzed by GC/MS. Data are mean ± SEM (n=3 cages) and were analyzed by 1-Way repeated measures ANOVA. Dunnett’s multiple comparison tests were used to determine differences from pretreatment fecal neutral sterols (Day 0, **p<0.01, ***p<0.001).
Fig SII. Effects of AdG5G8 on intestinal G5 and G5 protein levels (A), liver enzymes (B), and hepatic expression of inflammatory cytokines in obese, db/db mice. Values are mean ± SEM (n=4).
Figure SIII. AdG5G8 suppresses insulin signaling genes in obese mice. Total RNA was pooled from three db/db mice administered control virus or AdG5G8 and analyzed by PCR array. A) PCR Array layout with gene symbol, fold change and flags indicated. B) Heat Map of gene expression data. C) Genes with greater than a two-fold difference in abundance in AdG5G8 compared to controls are plotted by fold-change. # above bars indicates confirmation of significant difference by rtPCR in individual mice. Acaca upregulation could not be confirmed by rtPCR.
Figure SIV. Effect of AdG5G8 on ApoE. A) Immunoblot and densitometry analysis of serum ApoE in control and AdG5G8 treated mice. B, C) Total RNA was extracted from liver and small intestine 72 hr following viral administration and analyzed by rtPCR. Data are mean ± SEM (n=4)
Supplemental Figure V

Figure SV. Hepatic membrane proteins (50 µg) from LDL receptor deficient mice maintained on a chow or western diet for 16 weeks were isolated and subjected to SDS-PAGE and immunoblot analysis for G5 and G8. β-actin was used as a loading control.
Supplemental Methods

Reagents:

General chemicals were purchased from Sigma. Horseradish peroxidase conjugated secondary antibodies and SuperSignal West Pico Chemiluminiscent reagents were purchased from Thermo/Pierce. Real-time PCR reagents were purchased from Applied Biosystems. Calnexin, glucose-regulated protein 78-kD (GRP78), and glucose-regulated protein 94-kD (GRP94) antibodies were purchased from Nventa (San Diego, CA). Total and phospho-eIF2α, total and phospho-Akt, and β-actin antibodies were purchased from Santa Cruz. SREBP, insulin receptor and phospho-insulin receptor antibodies were purchased from Cell Signaling. The antibody to 3-hydroxy-3-methylglutaryl-CoA reductase (HMGCR) was purchased from Upstate. The SR-BI antibody was a kind gift from Deneys R. van der Westhuyzen (University of Kentucky). Production of ABCG5 and ABCG8 antibodies has been previously reported. Phospholipid, cholesterol and triglyceride (TG) assays were purchased from Wako Chemical (Richmond, VA).

Animals and Treatments

Male, db/db (stock #000697) mice and their lean littermates were obtained from Jackson Laboratory (Bar Harbor, ME). A second cohort of strain matched lean mice were also purchased from the same vendor (C57BL6/J, stock #000664). Mice were housed in individually ventilated cages and provided enrichment in the form of nesting material and acrylic huts. The animal room was set to a 14:10 hour dark/light cycle and a temperature of 22 ± 3°C. Upon arrival mice were allowed to adapt to the environment for a period of 7 days. All mice were maintained on standard rodent chow diet (Harlan Teklad 2014S). Where indicated, the chow diet was formulated with ezetimibe (0.005% w/w) by Research Diets Inc. (New Brunswick, NJ). All animal procedures conform to PHS policies for humane care and use of laboratory animals and were approved by the institutional animal care and use committee at the University of Kentucky.

Recombinant adenoviral vectors containing no insert (AdEmpty) and cDNAs for ABCG5 and ABCG8 have been described previously. Adenoviral vectors were amplified in HEK293Q cells, purified on cesium chloride gradients, and dialyzed against physiological saline. On Day 0 of the experiment mice were placed in clean cages and injected with a total of 5×10^11 particles/kg via the tail vein. After 72 hours (Day 3), mice were placed in clean cages and a fasting glucose was determined following a 4 hour fast beginning shortly after “lights-on” using blood obtained from a tail-vein prick and a standard glucometer. The animals were anesthetized with ketamine:xylazine anesthesia, blood, gall bladder bile, tissues and feces were collected. Serum was harvested by centrifugation. Tissues were snap frozen in liquid nitrogen and stored at -80°C until analyzed.

A glucose tolerance test (GTT) was conducted in an independent cohort of db/db mice as previously described. Mice were fasted for four hours beginning at “lights-on”. Mice were injected with 20% glucose solution (10 μl/ gram of body weight i.p.). In db/db mice, an insulin sensitivity test was also conducted. Fasted mice were administered human recombinant insulin (1 IU/kg i.p.). In both assays, blood glucose levels were measured prior to and 30, 60, 90 and 120 minutes following glucose and insulin injections. Areas under the curve (AUC) were calculated for blood glucose levels for each individual mouse. Triglyceride (TG) secretion rates were determined in a separate cohort of db/db mice (n=4). Mice were administered TritonWR-1339 (650 mg/kg body weight i.v). Blood was collected using
heparinized capillary tubes before and 0.5, 1, 2 and 3 h following injections.

**Analytical Procedures**

The preparation of membrane proteins, SDS-PAGE and immunoblotting were conducted as previously described. Real-time PCR and XBP-1 splicing assays were conducted as described previously. The Insulin Signaling Pathway PCR Array was purchased from QiAgen and conducted according to the manufacturer’s instructions.

Serum triglycerides and cholesterol in total and FPLC fractionated serum were measured with enzymatic colorimetric assays. Hepatic lipids were also determined using colorimetric assays following Folch extraction. Briefly, 100 mg of liver was ground using a Teflon pestle-glass homogenizer. Lipids were extracted in 2:1 chloroform:methanol at room temperature. The organic phase was dried under nitrogen gas, solubilized in 1 volume of 2% (v/v) Triton X-100 in chloroform, dried under streaming nitrogen, and solubilized in 2 volumes of water. Hepatic triglycerides, phospholipids and total cholesterol were normalized to wet tissue weight.

Fecal neutral sterols were analyzed as previously described. Total feces from the 72 hour period was collected, dried at 37°C, weighed and ground to powder. An aliquot of 0.125 g feces was placed into a glass tube with 1.25 ml ethanol and 0.25 ml 10N NaOH. Lipids were saponified at 72°C in a water bath for 2 hours and extracted (water, ethanol and petroleum ether, 1:1:1 v:v:v). 5α-cholestanol was used as internal standard. Following extraction, the organic phase was dried under a steam of nitrogen gas, and solubilized in hexane. The amount of neutral sterols (cholesterol, coprostanol and cholestanol) was quantified by GC/MS. Similarly, biliary cholesterol concentrations were determined by GC-MS from 5 ul of gallbladder bile following addition of the internal standard and Folch extraction.

**Statistical analysis**

Data are expressed as the mean ± SEM. Data were analyzed by two-way ANOVAs with genotype (lean vs. db/db) and treatment (control vs. AdG5G8) as factors. Bonferroni posttests were applied where indicated to determine differences due to genotype within control or AdG5G8 treated animals. Where only obese mice were considered, comparisons between control and AdG5G8 were conducted using a two-tailed t-test. Rates of TG secretion were determined by linear regression. Differences were considered significant at p < 0.05.

**Supplemental References**
