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ORIGINAL ARTICLE

Hepatocellular cystathionine γ lyase/hydrogen sulfide attenuates nonalcoholic fatty liver disease by activating farnesoid X receptor

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Abstract

Background and Aims: Hydrogen sulfide (H_2S) plays a protective role in NAFLD. However, whether cystathionine γ lyase (CSE), a dominant H_2S generating enzyme in hepatocytes, has a role in the pathogenesis of NAFLD is currently unclear.

Approach and Results: We showed that CSE protein expression is dramatically downregulated, especially in fibrotic areas, in livers from patients with NAFLD. In high-fat diet (HFD)-induced NAFLD mice or an oleic acid-induced hepatocyte model, the CSE/H_2S pathway is also downregulated. To illustrate a regulatory role for CSE in NAFLD, we generated a hepatocyte-specific *CSE* knockout mouse (CSE^{LKO}). Feeding an HFD to CSE^{LKO} mice, they showed more hepatic lipid deposition with increased activity of the fatty acid de novo

Abbreviations: 3-MST, 3-mercaptopyruvate sulfur transferase; ACC, acetyl-CoA carboxylase; ANOVA, analysis of variance; apoC, apolipoprotein C; BSEP, bile salt export pump; CBS, cystathionine β synthase; ChIP-qPCR, chromosome immunoprecipitation-quantitative PCR; CSE, cystathionine γ lyase; CYP7A1, cholesterol 7-alpha hydroxylase; FAS, fatty acid synthase; FXR, farnesoid X receptor; GO, Gene Ontology; H_2S, hydrogen sulfide; H&E, hematoxylin–eosin; HFD, high-fat diet; ITT, insulin tolerance test; LPL, lipoprotein lipase; LXR, liver X receptor; MAFG, v-maf musculoaponeurotic fibrosarcoma oncogene family protein G; MOI, multiplicity of infection; mRNA, messenger RNA; NaHS, Sodium hydrosulfide; OA, oleic acid; OCA, obeticholic acid; OGTT, oral glucose tolerance test; PTT, pyruvate tolerance test; RNA-seq, RNA-sequencing; SCD1, stearoyl-CoA desaturase 1; SHP, small heterodimer partner; SPP1, secreted phosphoprotein 1; SREBP-1c, sterol regulatory element binding protein 1c.

Wenjing Xu and Changting Cui contributed equally to this work.

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synthesis pathway, increased hepatic insulin resistance, and higher hepatic gluconeogenic ability compared to CSE^{Loxp} control mice. By contrast, H_2S donor treatment attenuated these phenotypes. Furthermore, the protection conferred by H_2S was blocked by farnesoid X receptor (*FXR*) knockdown. Consistently, serum deoxycholic acid and lithocholic acid (FXR antagonists) were increased, and tauro-β-muricholic acid (FXR activation elevated) was reduced in CSE^{LKO}. CSE/H_2S promoted a post-translation modification (sulfhydration) of FXR at Cys138/141 sites, thereby enhancing its activity to modulate expression of target genes related to lipid and glucose metabolism, inflammation, and fibrosis. Sulfhydration proteomics in patients' livers supported the CSE/H_2S modulation noted in the CSE^{LKO} mice.

Conclusions: FXR sulfhydration is a post-translational modification affected by hepatic endogenous CSE/H_2S that may promote FXR activity and attenuate NAFLD. Hepatic CSE deficiency promotes development of nonalcoholic steatohepatitis. The interaction between H_2S and FXR may be amenable to therapeutic drug treatment in NAFLD.

INTRODUCTION

NAFLD is a common chronic liver disease characterized by lipid accumulation in hepatocytes (steatosis) with or without inflammation (NASH).[1] NAFLD not only contributes to the development of cirrhosis, hepatocellular carcinoma, and type 2 diabetes mellitus but is also associated with an increased risk of developing cardiovascular events.[2]

Nuclear receptors such as peroxisome proliferator-activated receptors (PPARs), liver X receptor (LXR), and farnesoid X receptor (FXR) play a crucial role in the pathogenesis of NAFLD.[3] Targeting nuclear receptors, such as FXR with the agonist obeticholic acid (OCA; which is approved by the Food and Drug Administration to treat cholestatic liver diseases) may attenuate liver inflammation and steatosis and enhance insulin sensitivity.[4,5] Although this drug has some side effects, such as pruritus and increases in plasma low density lipoprotein cholesterol, OCA is a promising drug for the treatment of NASH.[6]

Hydrogen sulfide (H_2S) is a gas transmitter that is dependent on cystathionine β synthase (CBS), cystathionine γ lyase (CSE), or 3-mercaptopyruvate sulfur transferase (3-MST) activity in the liver.[7] CSE protein exceeds CBS protein by about 60-fold in mouse liver, and about 90% H_2S biosynthetic activity might be sourced from CSE.[8] In a high-fat diet (HFD)–induced NAFLD mouse model, hepatic CSE/H_2S is significantly downregulated.[9,10] By contrast, H_2S donor lowers HFD-induced steatosis and serum triglyceride concentrations by adenosine 5'-monophosphate (AMP)-activated protein kinase (AMPK)-mammalian target of rapamycin (mTOR) mediated hepatocyte autophagy[11] or by inhibition of hepatic acetyl-CoA activity.[12] Furthermore, inhibition of 3-MST reduced HFD-induced NAFLD by upregulating the CSE/H_2S pathway.[13] Dietary methionine restriction or physical exercise may also attenuate HFD-induced hepatic lipid accumulation by enhancing the CSE/H_2S pathway.[14,15] More interestingly, H_2S donor modulated PPARγ activity in HFD mice[16] and reduced low density lipoprotein receptor independent of LXR activity,[17] which may be relevant in NAFLD. Thus, these studies highlight a potential preventative role of CSE/H_2S in NAFLD and also raise the following two main research questions: what are the relevant CSE/H_2S changes in patients with NAFLD, and what is the role of hepatic endogenous CSE/H_2S regulation in NAFLD?

In the present experimental study, we have compared liver CSE expression in subjects with and without NAFLD. We then confirmed these changes in liver CSE expression both in HFD-induced NAFLD mouse liver and in oleic acid (OA)-stimulated primary mouse hepatocytes. In a hepatocyte-conditional CSE knockout mouse model, we also compared the liver lipid deposition changes involving FXR regulation.

PATIENTS AND MATERIALS

Patients

A total of 23 non-NAFLD individuals and 22 age- and sex-matched patients with NAFLD who had undergone liver biopsy were recruited at the First Affiliated Hospital of Wenzhou Medical University. The inclusion criteria of the study were as follows: patients with obesity undergoing bariatric surgery with no prior evidence of liver diseases. Liver biopsy was performed

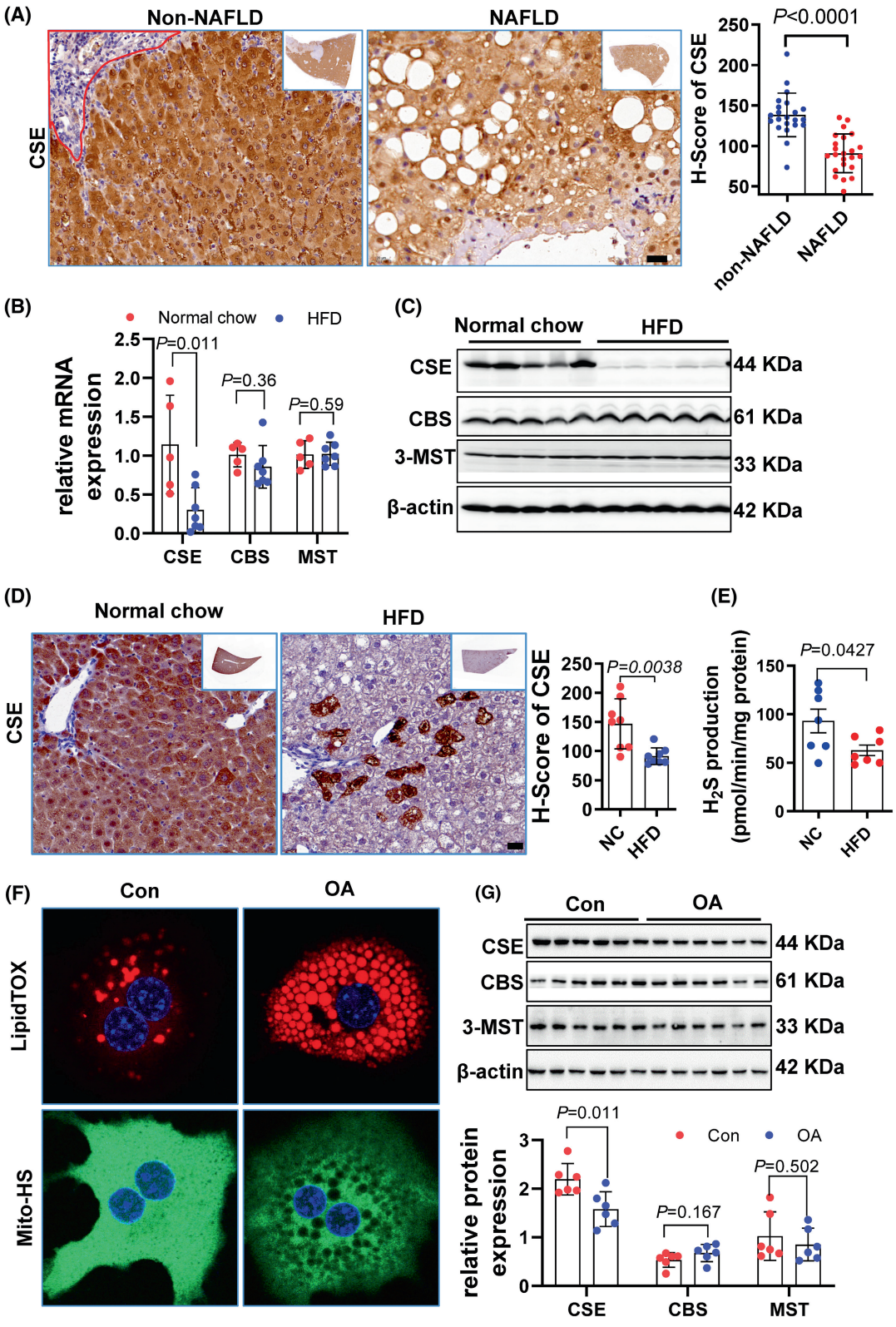


FIGURE 1 Downregulation of hepatic cystathionine γ lyase (CSE)/hydrogen sulfide (H_2S) in patients and mice with NAFLD. (A) Immunohistochemistry (IHC) staining of CSE in liver biopsy from patients with and without NAFLD. Protein expression was evaluated by an H-score semiquantitative approach. Bar = 20 μm. Red line area is a fibrotic area. There is no positive CSE staining in this area. (B) Endogenous H_2S generation key enzymes: cystathionine β synthase (CBS), CSE, and 3-mercaptopyruvate sulfur transferase (3-MST) messenger RNA (mRNA) expression, protein expression by western blot (C) or IHC staining, bar = 20 μm (D) in high-fat diet (HFD)-induced NAFLD mice. *N* = 5. (E) H_2S generation ratio of mouse liver tissue was measured by methylene blue assay. *N* = 7–8. (F) Oleic acid (OA; 400 μM) treated primary mouse hepatocytes for 48 h, LipidTox staining for lipid deposition, Mito-HS for H_2S production. (G) CBS, CSE, and 3-MST protein expression were measured in OA-treated hepatocytes. *N* = 6.

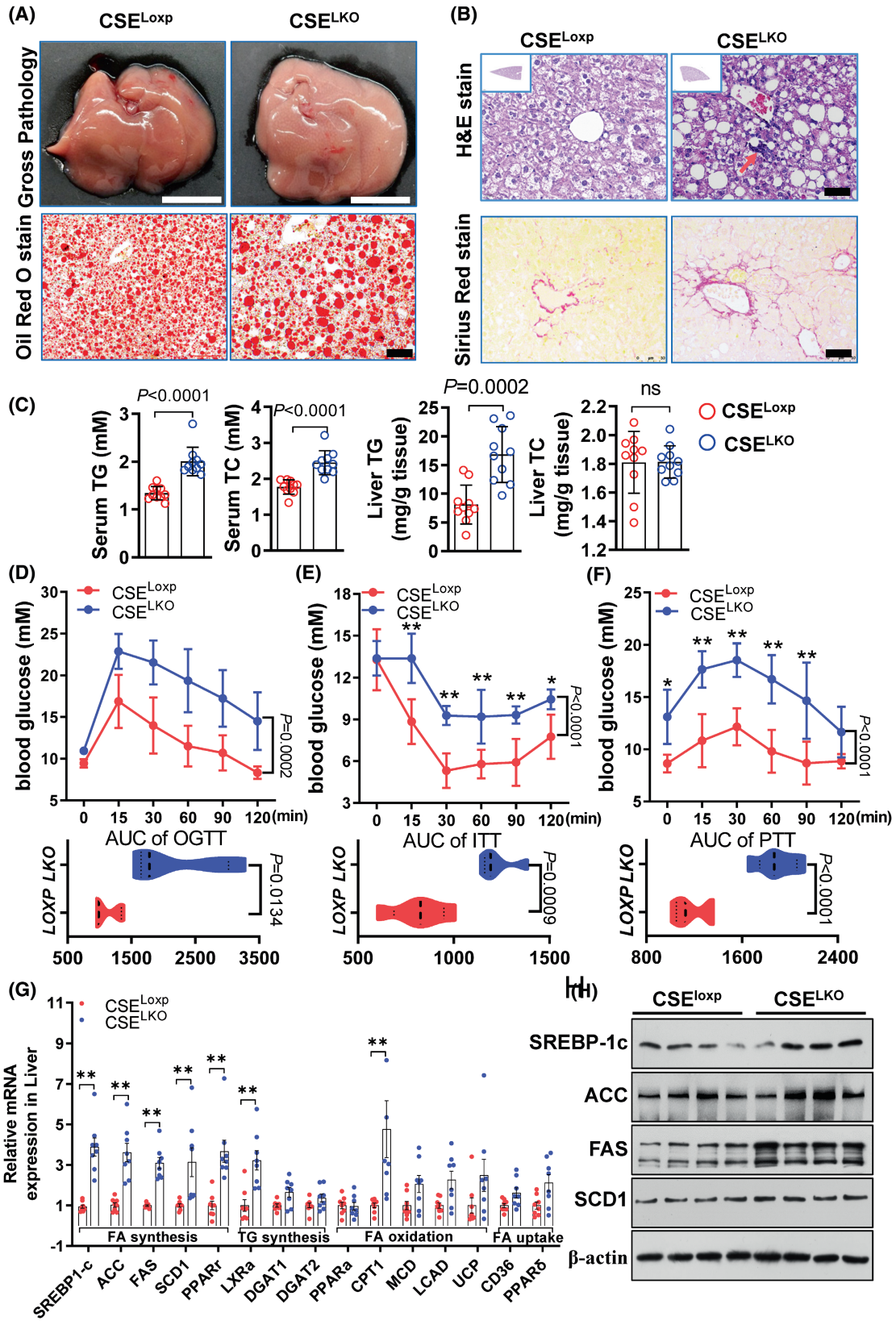


FIGURE 2 Hepatic cystathionine γ lyase (*CSE*) deletion mice exacerbated high-fat diet (HFD)-induced NAFLD. (A) General pathology (bar = 1 cm) and Oil Red O staining (bar = 50 μm) for liver tissues in hepatic CSE-specific knockout mice (CSE^{LKO}) and control loxp/loxp mice (CSE^{Loxp}). (B) Hematoxylin–eosin (H&E) and Sirius Red staining for liver tissues. Bar = 50 μm. (C) Liver triglyceride (TG) and total cholesterol (TC) levels in NAFLD mice. (D) Oral glucose tolerance test (OGTT), (E) insulin tolerance test (ITT), (F) and pyruvate tolerance test (PTT) were compared between CSE^{LKO} and CSE^{Loxp}. N = 8–10 in all animal experiments. (G) Lipid metabolism–related genes expression was assayed by quantitative real-time PCR. N = 6. $^{**}p < 0.01$. (F) Fatty acid de novo synthesis–related protein expression was detected by western blot. N = 6.

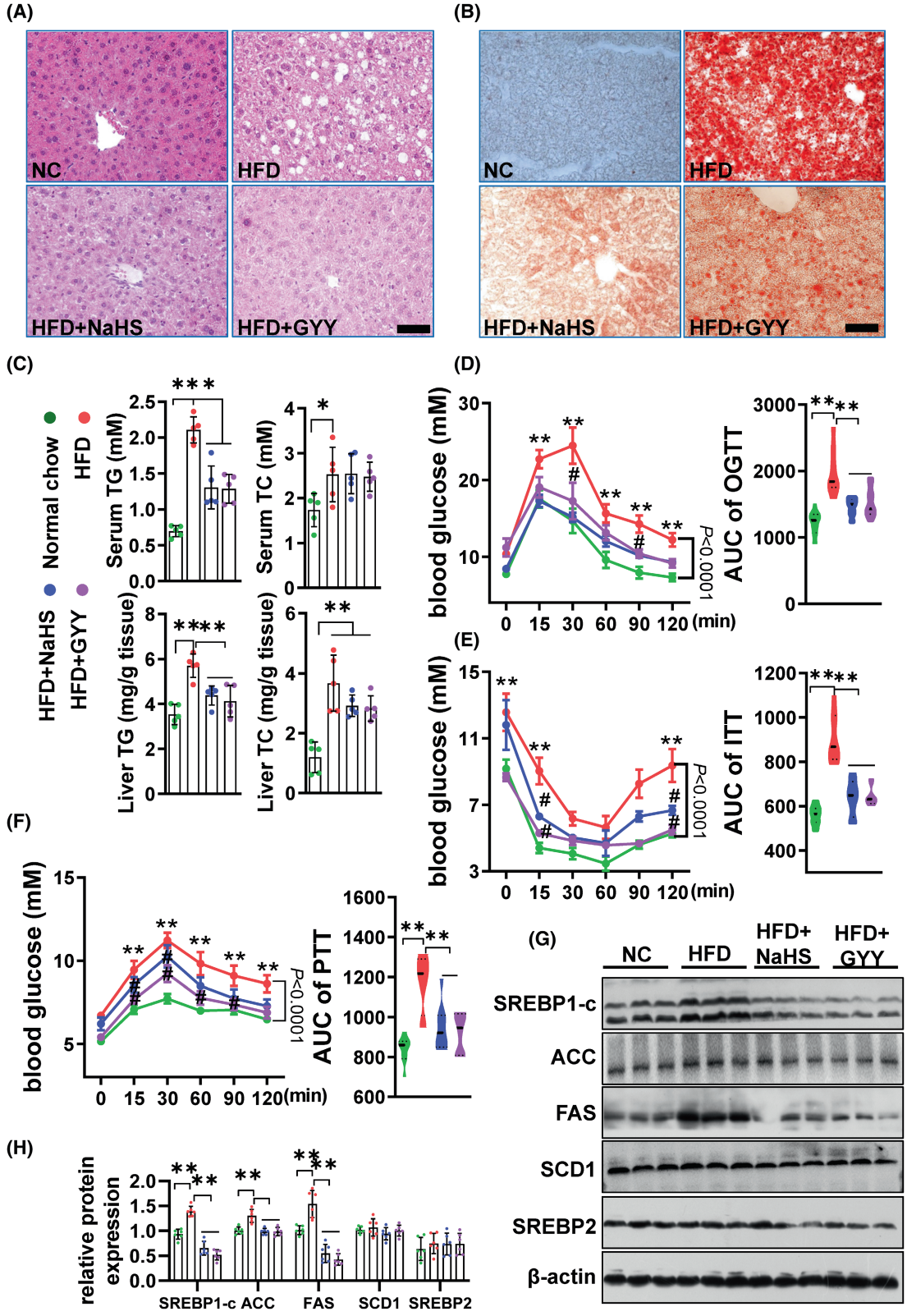


FIGURE 3 Hydrogen sulfide (H_2S) donor treatment ameliorated high-fat diet (HFD)-induced NAFLD and glucose metabolism disorder. In HFD-induced NAFLD mouse model, H_2S donor-NaHS or GYY4137 treatment for 12 weeks, then hematoxylin–eosin (H&E) staining (A), Oil Red O staining (B) was used for evaluation the lipid deposition in liver. Bar = 50 μm. (C) Changes of serum triglycerides (TG), total cholesterol (TC), and liver TG, TC level after H_2S donor treatment. *$p < 0.05$; **$p < 0.01$. (D) Oral glucose tolerance test (OGTT), (E) insulin tolerance test (ITT), and (F) pyruvate tolerance test (PTT) changes after H_2S donor treatment. Two-way mixed effect analysis of variance (ANOVA) was used, **$p < 0.01$ vs. normal chow, $^{\#}p < 0.05$ vs. HFD. (G) Fatty acid de novo synthesis–related protein expression by western blot. (H) The semiquantitative analysis of above proteins by relative gray density plus area of target protein comparison to β-actin. **$p < 0.01$. Six independent experiments were performed.

during the bariatric procedure. Exclusion criteria of the study were as follows: current excessive drinking (average daily consumption of >20 g alcohol/day for women and >30 g alcohol/day for men); chronic use of potential hepatotoxic drugs; viral hepatitis; or haemochromatosis.[18] Written informed consent was obtained from each patient. The study protocol conformed to the ethical guidelines of the 1975 Declaration of Helsinki as reflected in a priori approval by the ethics committees of the First Affiliated Hospital of Wenzhou Medical University (No. 2016–0246).

Animal model

Wild-type mice were purchased from the Animal Center, Fuwai Hospital. *CSE*$^{flox/flox}$ (*CSE*^{Loxp}) mice (C57BL/6J background) were generated by inserting loxP sites between exon 1 and 4 of *CSE* genes (Figure S1). Liver *CSE* conditional knockout (*CSE*^{LKO}) mice were generated by hybridizing *CSE*^{Loxp} mouse with an albumin promoter-driven Cre recombinase transgenic mouse. Male C57BL/6J mice, *CSE*^{Loxp} and *CSE*^{LKO} mice (sibling littermates) aged 8 weeks were fed with an HFD (60 kcal% fat, Research Diets D12492, USA) for 12 weeks to induce NAFLD in the animal model. A normal chow diet (Research Diets 12,450 J) was used as the control diet. Two H_2S donors, i.e., Sodium hydrosulfide (NaHS) (50 mg/kg/day) and GYY4137 (46 mg/kg/day), or vehicle (normal saline, 0.1 ml/day) treatments were given by intraperitoneal injections.

The mice were housed under a 12-h light/dark cycle with ad libitum access to food and water. All animal experiments were approved by the Ethics Committee on Animal Care of Fuwai Hospital, and the investigation complied with the animal Management Rule of the Ministry of Health, People's Republic of China (Document No. 55, 2001) and Guide for the Care and Use of Laboratory Animals of the US National Institutes of Health.

Statistical analysis

Data are expressed as means and SD. Normality of the data distribution was checked by the Kolmogorov Smirnov test. Differences between groups were evaluated with the unpaired Student *t* test. For three or more groups, data were compared by using the one-way analysis of variance (ANOVA), followed by Tukey post-hoc analysis. Comparisons including two factors were performed by two-way ANOVA. Repeated measures on the same animals were analyzed using two-way mixed-effects ANOVA. All statistical analysis involved using GraphPad Prism v8.0.2. $p<0.05$ was considered statistically significant.

NB: For other methods and material details, see the expanded Methods section in the Online Data Supplement.

RESULTS

Downregulation CSE/H_2S in patients with NAFLD and mice

Because liver expresses CSE, CBS, and 3-MST enzymes, we confirmed that *CSE* (5.8-fold increase compared to *CBS*, and 48.9-fold increase compared to *3-MST*, Figure S1B) is the dominant H_2S generation enzymes in mouse liver tissues. We performed immunohistochemical staining for CSE and CBS in both 23 patients with NAFLD (steatosis confirmed by hematoxylin–eosin [H&E] staining, Figure S2A) and 22 non-NAFLD individuals (see Table S1), who underwent liver biopsy.

In the livers of these patients with NAFLD, hepatic CSE expression was significantly downregulated by about 33% compared to that in non-NAFLD patients' livers (Figure 1A). CBS protein was not changed (Figure S2B). More intriguingly, the CSE protein in the liver fibrotic area was markedly decreased (Figure 1A). To confirm this, we also measured the CSE/H_2S changes in HFD-induced NAFLD mouse liver. In keeping with the aforementioned changes in patients with NAFLD, *CSE* messenger RNA (mRNA; Figure 1B) and protein expression was decreased (Figures 1C and S3) and confirmed by immunohistochemical staining (Figure 1D) in HFD mouse liver, without changes in CBS (Figure S4) and 3-MST (Figure 1C) expression. Coinciding with CSE downregulation, hepatic H_2S generation was also reduced (about 33%) in HFD mice (Figure 1E).

To investigate whether the CSE/H_2S downregulation was stimulated by lipid deposition, we treated primary mouse hepatocytes with OA (400 μM) for 24 h. LipidTox staining showed abundant intracellular lipid droplets associated with a reduction in H_2S generation (mito-HS staining, Figure 1F). Accordingly, only CSE, but not CBS or 3-MST protein, was decreased in OA-stimulated cells (Figure 1G). These results suggest that hepatic lipid deposition was associated with CSE/H_2S reduction.

Hepatic CSE/H_2S attenuated HFD-induced steatosis and insulin resistance

To evaluate the role for hepatic CSE/H_2S in NAFLD, we constructed hepatic-conditional *CSE* knockout mice (*CSE*^{LKO}) by loxp/cre recombination system (Figure S1A). This mouse model confirmed CSE deletion in hepatocytes by CSE mRNA and protein expression (Figure S1C), and there was a ~75% decrease in H_2S generation in liver tissues (Figure S1D). Because the CSE global knockout caused hyperhomocysteinemia, we also measured serum homocysteine and cysteine levels and confirmed that hepatocyte-specific deletion of CSE did not induce CBS mRNA expression

FIGURE 4 Hepatocellular endogenous cystathionine γ lyase (CSE)/hydrogen sulfide (H_2S) upregulated farnesoid X receptor (FXR) expression. Total RNA was extracted from about 30 mg liver tissue of CSE^{LKO} or CSE^{Loxp} mice, then bulk RNA-sequencing was performed. (A) Volcano plot shows the downregulated genes (blue) and upregulated genes (red) in CSE^{LKO} compared with CSE^{Loxp} mice. Open circles represent the Gene Ontology (GO)-enriched genes. (B) GO analysis shows the changed genes enrichment in the major pathway. (C) FXR protein expression in *CSE* knockout liver tissues. $N = 6$. (D) Hepatic FXR protein level changes after H_2S donor treatment. With overexpression *CSE* by adenovirus or knockdown *CSE* by siRNA in hepG2 cells, the FXR messenger RNA (mRNA) (E) and protein expression (F) change. $N = 6$. Then, the fatty acid de novo synthesis–related genes: sterol response element binding protein 1c (*SREBP-1c*), acetyl-CoA carboxylase (*ACC*), fatty acid synthase (*FAS*), and stearoyl-CoA desaturase 1 (*SCD1*) mRNA ($N = 4$) (G) and protein expression (H) changes associated with CSE overexpression or knockdown. $^*p < 0.05$; $^{**}p < 0.01$. $N = 6$.

(Figure S5A) or cause hyperhomocysteinemia but lowered cysteine synthesis (Figure S1E). Feeding an HFD for 12 weeks, the CSE^{LKO} mice developed more severe hepatic steatosis compared to control mice (CSE^{Loxp}) (Figure 2A). H&E and Sirius Red staining showed hepatocyte ballooning with Mallory-Denk bodies, lobular inflammation, and heightened collagen fiber in CSE^{LKO} liver (Figure 2B), thus indicating that these mice are prone to developing NASH. In line with hepatic lipid deposition, serum and liver triglyceride levels and serum total cholesterol levels were increased in CSE^{LKO} mice (Figure 2C). Oral glucose tolerance tests (OGTT; Figure 2D), intravenous insulin tolerance tests (ITT; Figure 2E), and pyruvate tolerance tests (PTT; Figure 2F) in CSE^{LKO} mice indicated that *CSE* deficiency exacerbated both glucose homeostasis and insulin resistance.

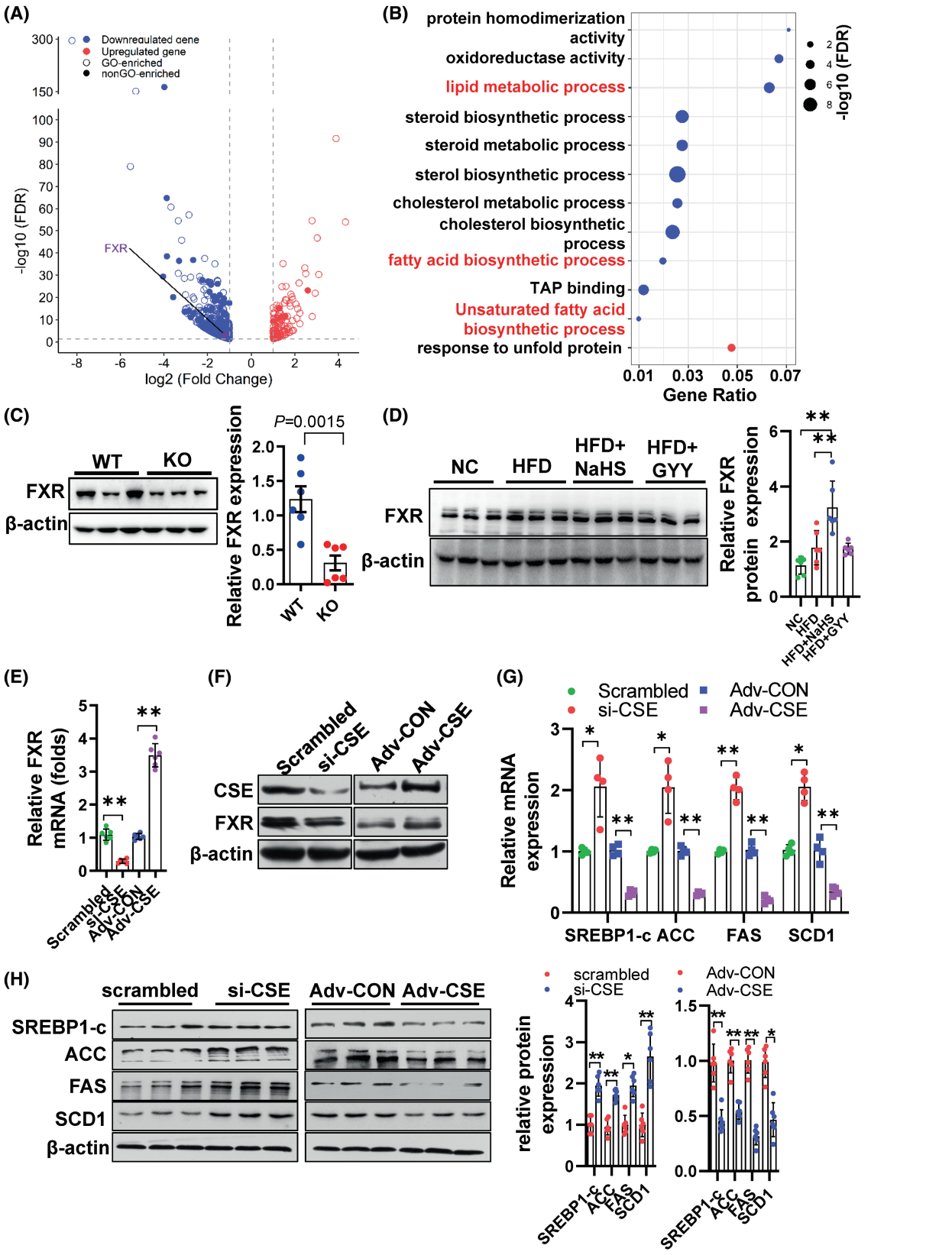
To investigate the major pathophysiological processes in CSE/H_2S on liver lipid metabolism, we screened the essential regulatory genes, including fatty acid de novo synthesis, triglyceride synthesis, fatty acid oxidation, and fatty acid uptake by quantitative real-time PCR. As shown in Figure 2G, most regulated genes were fatty acid de novo synthetic genes in CSE^{LKO} liver. These genes coding proteins (sterol response element binding protein 1c [SREBP-1c], acetyl-CoA carboxylase [ACC], fatty acid synthase [FAS], stearoyl-CoA desaturase 1 [SCD1]) were also increased in CSE^{LKO} mice (Figures 2H and S5B). In primary hepatocytes, *CSE* deficiency also increased lipid droplets, which were reversed by NaHS supplementation (Figure S6). These loss of function experiments indicate that hepatic *CSE* deletion exacerbated HFD-induced steatosis and insulin resistance, in part via enhancing fatty acid de novo synthesis, and increased risk of NASH.

In contrast, we treated HFD-induced NAFLD mice with two H_2S donors: NaHS (50 mg/kg/day) and GYY4137 (46 mg/kg/day) by intraperitoneal injections. HFD model mice received equal volumes of normal saline injection. After treating for 12 weeks, H_2S donors dramatically attenuated HFD-induced steatosis by H&E (Figure 3A) and Oil Red O staining (Figure 3B) analysis. H_2S donor treatment also lowered serum and liver triglyceride levels, and liver cholesterol levels (Figure 3C). OGTT (Figure 3D), ITT (Figure 3E), and PTT (Figure 3F) data showed downregulation of fatty acid de novo synthesis-associated genes: *SREBP-1c*, *ACC*, *FAS*, and *SCD1*. Protein expression was also lowered after H_2S donor treatment (Figure 3G,H). Therefore, the loss of function and donors' treatment experiments highlighted hepatic CSE/H_2S protection in NAFLD.

CSE/H_2S attenuated steatosis by FXR

To further clarify the possible molecular mechanism(s) of CSE/H_2S protection in steatosis development, we performed liver transcriptome analysis in both CSE^{LKO} and CSE^{LOXP} mice. Here, we identified 151 upregulated and 561 downregulated genes, and the heatmap graph is shown in Figure S7A and the volcano plot in Figure 4A. Gene Ontology (GO) enrichment genes included cholesterol, sterol, lipid, fatty acid metabolism, and biosynthesis pathway (Figure 4B). By STRING function protein association network analysis, we focused on an essential metabolic nuclear receptor, FXR, in NAFLD (Figure S7B). Liver FXR protein expression was markedly reduced in CSE^{LKO} mice (Figure 4C), but it was upregulated after NaHS treatment (Figure 4D). Consistently, knockdown CSE decreased, and overexpression of CSE increased FXR mRNA (Figure 4E) and protein levels (Figures 4F and S8A). H_2S donor treatment of primary hepatocytes also increased FXR protein expression (Figure S8B). In line with FXR expression and activation, some essential genes involved in fatty acid de novo synthesis: *SREBP-1c*, *ACC*, *FAS*, and *SCD1* mRNA (Figure 4G) and protein (Figure 4H) expression also showed inverted changes associated with CSE knockdown or overexpression.

To confirm a role for FXR in CSE/H_2S protection, we designed and identified a small interference RNA of *FXR* (Figure S9A). We then constructed and purified the knockdown *FXR* lentivirus, which effectively lowered the FXR protein level (Figure S9B) in primary mouse hepatocytes. By scrambled RNA-green fluorescence protein control lentivirus transfection into hepatocytes (Figure S9C), we counted the multiplicity of infection (MOI) of the virus. Next, we injected control lentivirus (10 MOI) by tail vein and confirmed the transfection efficiency in vivo (Figure S9D). Using lentivirus knockdown hepatic *FXR*, more severe hepatic steatosis developed with HFD-induction, which abolished the protective effect of the H_2S donor on steatosis (Figure 5A). In addition, knockdown FXR also blocked the H_2S protection on triglyceride, cholesterol, and glucose metabolism (Figure 5B): OGTT (Figure 5C), ITT (Figure 5D), and



PTT (Figure 5E), respectively. For mechanism, H_2S-attenuated fatty acid de novo synthesis (Figure 5F,G) were also blocked, while FXR knocked down. We also measured the FXR target genes HMG-CoA reductase (*HMGCR*), apolipoprotein C (*apoC*)-II, small heterodimer partner (*SHP*), v-maf musculoaponeurotic fibrosarcoma oncogene family protein G (*MAFG*), cholesterol 7-alpha hydroxylase (*CYP7A1*), and lipoprotein lipase (*LPL*) expression in liver tissues and confirmed activation FXR by H_2S treatment (Figure S10).

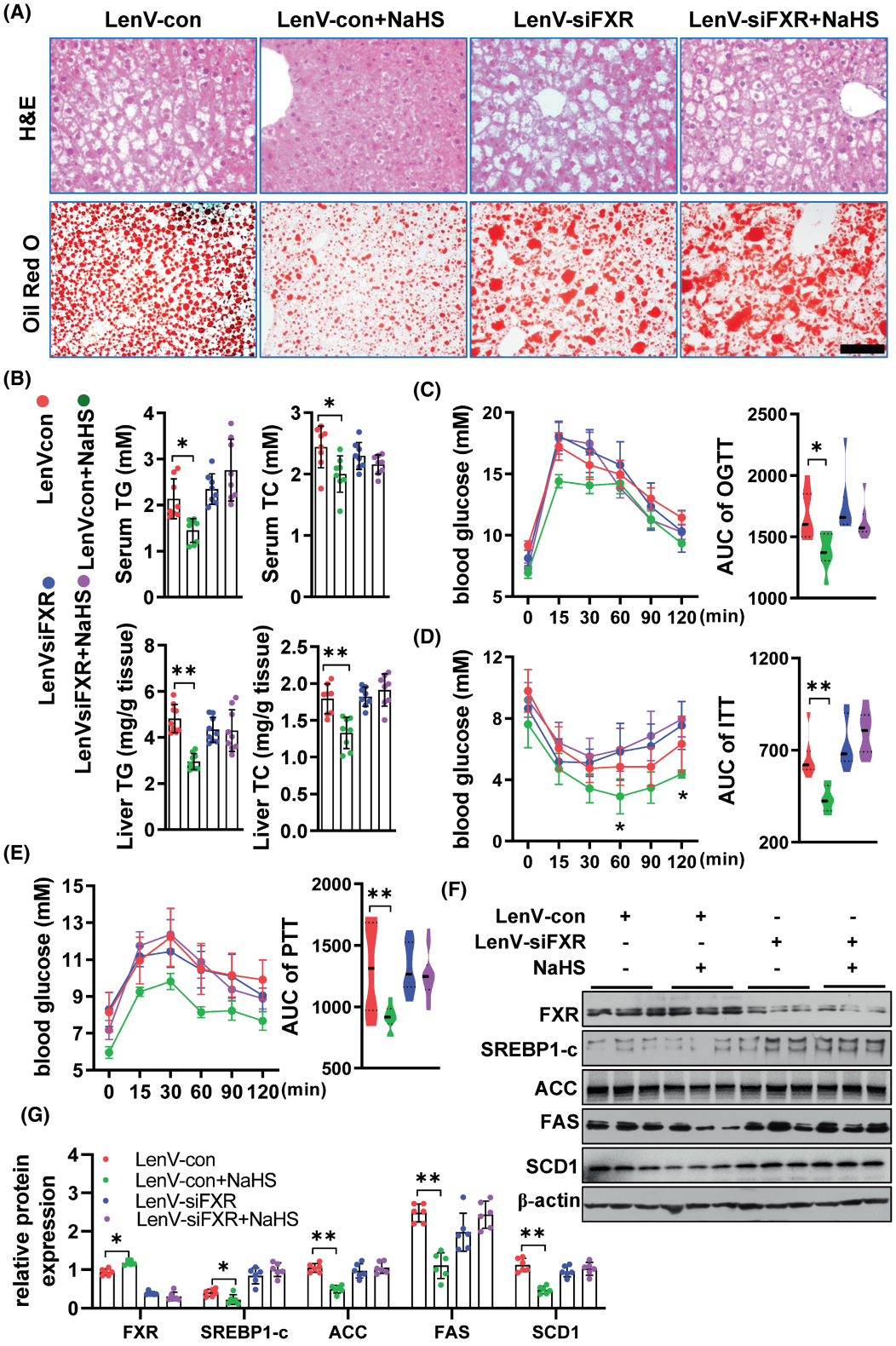


FIGURE 5 Knockdown farnesoid X receptor (FXR) by lentivirus blocked hydrogen sulfide (H_2S) donor's protection on NAFLD. Knockdown FXR shRNA lentivirus (10 multiplicity of infection [MOI]) was bolus injected by tail vein before high-fat diet (HFD) feeding. Continue feeding HFD for 12 weeks; hematoxylin–eosin (H&E) staining for liver tissue morphology, Oil Red O staining for hepatic lipid deposition. Bar = 100 μm (A). (B) Serum and liver triglycerides (TG), total cholesterol (TC) level were measured. *$p < 0.05$, **$p < 0.01$. (C) Oral glucose tolerance test (OGTT), (D) insulin tolerance test (ITT), and (E) pyruvate tolerance test (PTT) were assayed for glucose metabolism. *$p < 0.05$, **$p < 0.01$. $N = 8$ in this animal experiment. (F) Hepatic FXR protein, fatty acid de novo synthesis genes: sterol response element binding protein 1c (SREBP-1c), acetyl-CoA carboxylase (ACC), fatty acid synthase (FAS), and stearoyl-CoA desaturase (SCD) protein expression was detected by western blot. $N = 6$. (G) The semiquantitative analysis of above proteins. *$p < 0.05$, **$p < 0.01$.

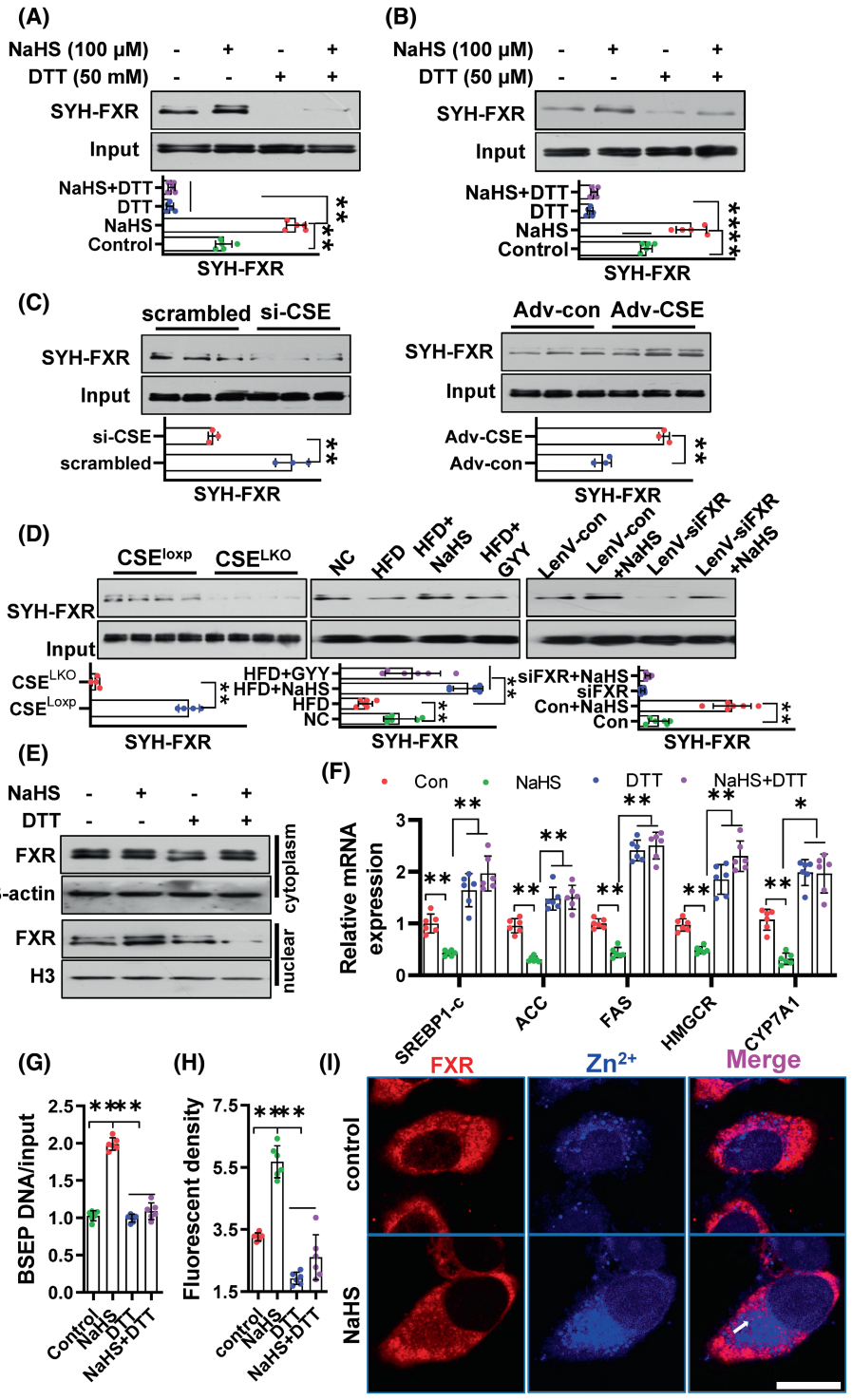


FIGURE 6 Cystathionine γ lyase (CSE)/hydrogen sulfide (H_2S) sulfhydrated farnesoid X receptor (FXR) and promoted its binding to Zn^{2+}, then enhanced its activity. (A) Biotin-switch assay for FXR sulfhydration in vitro. (B) HepG2 cells were treated with NaHS or DTT, followed by FXR immunoprecipitation using antibody, and then biotin-switch assay was performed for FXR sulfhydration in vivo. $N = 5$. (C) Knockdown or overexpressed CSE; intracellular FXR sulfhydration level changes. $N = 3$. (D) Alterations of hepatic FXR sulfhydration in animal model, including in *CSE*^{LKO} and *CSE*^{Loxp}, H_2S donor's treatment model and FXR knockdown model. $N = 4–6$. (E) Nuclear FXR translocation was detected, while sulfhydrated FXR by NaHS or desulfhydrated FXR by DTT. $N = 6$. (F) FXR sulfhydration dependent transcription activity was evaluated by FXR associated or target genes expression. $N = 8$. (G) ChIP-quantitative PCR (qPCR) identified the FXR binding activity to bile salt export pump (*BSEP*; a well-known FXR target gene) promoter while FXR sulfhydration or desulfhydration. $N = 6$. (H) Using Histidine-tagged and Nickle sepharose system to purify FXR, then 1 μg FXR incubation with NaHS or DTT, Zn^{2+} and Zn^{2+}-probe for 30 min, after washing, the FXR-Zn^{2+} binding was detected by fluorescence density count. $N = 6$. (I) In vivo FXR-Zn2+ binding was shown by cofluorescence of FXR (red) and Zn^{2+} probe (blue), as indicated by the white arrow. In this figure, $^*p < 0.05$, $^{**}p < 0.01$.

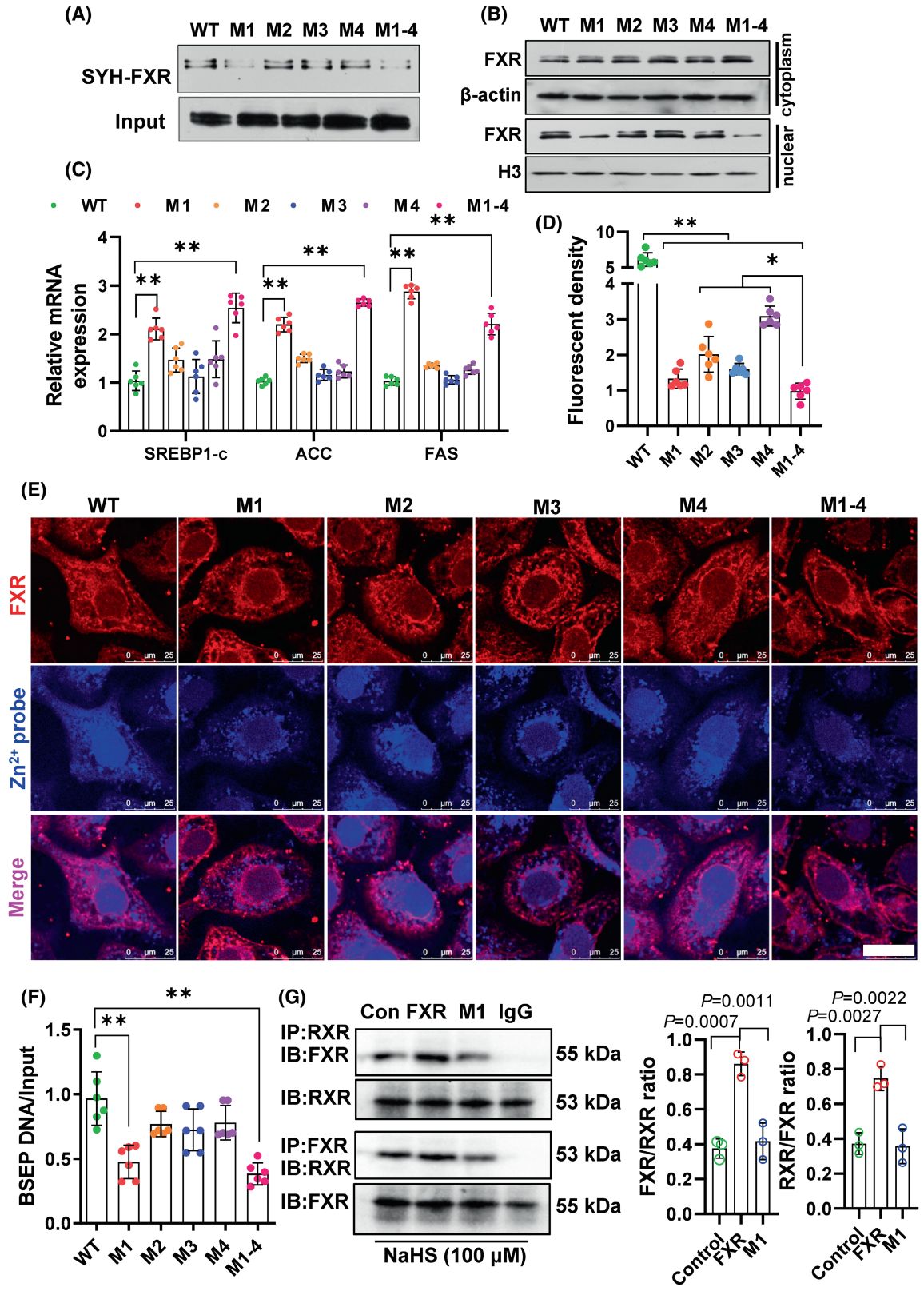


FIGURE 7 Identify the farnesoid X receptor (FXR) sulfhydration sites. Mutation 4 zinc finger areas named M1, M2, M3, M4, or all mutations (M1–4) of FXR, then these plasmids are transfected into 293-HEK cells. (A) The changes of FXR sulfhydration in different mutation sites. $N = 5$. (B) The different mutation effect on FXR nuclear translocation. $N = 5$. (C) These mutations on hydrogen sulfide (H_2S)-mediated sterol response element binding protein 1c (SREBP-1c), acetyl-CoA carboxylase (ACC), and fatty acid synthase (FAS) messenger RNA (mRNA) expression. Different mutation sites on H_2S-mediated FXR-Zn^{2+} binding activity in vitro (D) or in vivo (E). $N = 6$. H_2S regulated FXR binding to promoter of bile salt export pump (BSEP) by Chromosome immunoprecipitation (ChIP)-quantitative PCR (qPCR) (F). (G) Coimmunoprecipitation (co-IP) assay for FXR and RXR interaction and H2S donor treatment in FXR or M1 transfected cells. In this figure, $^*p < 0.05$, $^{**}p < 0.01$. $N = 6$.

By contrast, the FXR target genes *SHP*, *MAFG*, and bile salt export pump (*BSEP*) were downregulated, and *CYP7A1* was upregulated in the liver of CSE^{LKO} mice compared to that observed in CSE^{LOXP} mice (Figure S11). Because FXR is a bile acid metabolism–related receptor, we measured serum bile acid compositions. As Figure S12A shows, the serum bile composition was different between CSE^{LKO} and CSE^{LOXP} mice. Interestingly, serum FXR antagonistic bile acids lithocholic acid and deoxycholic acid were increased (similar to patients with NAFLD[19]), whereas tauro-β-muricholic acid (increased by FXR agonist[20]) was decreased in CSE^{LKO} mice (Figure S12A,B). These results indicate that hepatic CSE/H_2S may ameliorate steatosis in part via FXR activation.

CSE/H_2S sulfhydrates FXR to increase Zn^{2+} binding and promote FXR activity

FXR is a zinc finger protein that has two conserved C4 zinc fingers in its DNA binding domain (Figure S13). Zinc binding protein such as sirtin-1 could be sulfhydrated by H_2S and activating its deacetylation activity.[21] Therefore, we investigated whether the sulfhydration of FXR affects its activity. Treatment with NaHS caused FXR sulfhydration as identified in vitro (mouse liver tissues homogenate; Figure 6A) and in vivo (primary mouse hepatocytes; Figure 6B). Knockdown of CSE decreased (Figure 6C), and by contrast overexpression of CSE increased FXR sulfhydration (Figure 6D). In keeping with changes in cellular FXR sulfhydration, sulfhydrated FXR in CSE^{LKO} liver tissues was dramatically decreased in comparison to that of CSE^{LOXP}. FXR sulfhydration was also reduced in NAFLD mice liver tissues and was rescued by the H_2S donors (NaHS or GYY) (Figure 6D). In patients, we confirmed FXR sulfhydration in two non-NAFLD patients' liver samples, but none in patients with NAFLD (Figure S14A). These results highlight that FXR could be sulfhydrated by CSE/H_2S, which in turn downregulates lipid deposition.

To investigate protein sulfhydration in NAFLD development, we measured the sulfhydrated proteomics of patients. Using biotin-switch assays, we identified 160 sulfhydrated proteins in the liver tissues of five patients with NAFLD and 246 proteins in five non-NAFLD patients. There were 106 proteins that overlapped between the two patient groups. Metascape GO networks analysis showed that overlapped gene were enriched for fatty acid metabolism, monocarboxylic acid metabolism, sulfur amino acid metabolism, reactive oxygen species, and protein folding (Figure S14B). This proteomics analysis indicates CSE/H_2S determines protein sulfhydration including FXR and may play an important role in NASH.

To elucidate whether FXR sulfhydration was associated with its transcription activity, we first detected FXR nuclear translocation. As Figures 6E and S15A indicate, sulfhydrated FXR mediated by NaHS significantly increased nuclear translocation. Conversely, removing FXR sulfhydration with DTT reduced nuclear translocation. Correspondingly, fatty acid synthesis–related genes (*SREPB-1c*, *FAS*, and *ACC*), cholesterol synthesis genes (*HMGCR*), and *CYP7A1* were downregulated with FXR sulfhydration and were upregulated after removing sulfhydration (Figure 6F). Chromosome immunoprecipitation (ChIP)-quantitative PCR data also confirmed that sulfhydration enhanced FXR binding to BSEP promoter, and desulfhydration lowered it (Figures 6G and S15B). Consistent with these data, sulfhydration increased FXR and Zn^{2+} binding, whereas desulfhydration decreased it (Figure 6H,I). These data indicate that CSE/H_2S sulfhydrates FXR and increased its binding to Zn^{2+}, thereby promoting its nuclear translocation, DNA binding activity, and transcription regulation.

Because there were two conserved Zn^{2+} binding domains in FXR, we next identified the sulfhydration sites by mutation of major cysteine residue sites. We constructed five mutation plasmids targeting four CXXC domain as shown as Figure S13. We coexpressed FXR/FXR mutation, RXR, and *BSEP* promoter luciferase report plasmids in 293-HEK cells, then demonstrated that all five mutations lowered FXR interaction with the *BSEP* promoter (Figure S16A), suggesting that Zn^{2+} binding is essential for FXR activity. By biotin-switch assays, Cys138/141 double mutation and all eight cysteine residue sites mutation dramatically reduced FXR sulfhydration (Figures 7A and S16B), suggesting Cys138/141 of FXR as a major sulfhydration site. In line with sulfhydration lowering, H_2S-promoted FXR nuclear translocation was reduced in M1 and M1–4 mutations (Figures 7B and S16C). FXR sulfhydration–regulated fatty acid de novo synthesis–related genes (*SREBP-1c*, *FAS*, and *ACC*) expression (Figure 7C), binding to Zn^{2+} (Figure 7D,E), and *BSEP* promoter binding activity (Figures 7F and S16D) were also blocked by M1 and M1–4 mutation. Coimmunoprecipitation assay also showed M1 mutation reduced FXR interaction with the RXR protein (Figure 7G). For functional analysis, treating 293-HEK cells with OA (200 μM) and NaHS (100 μM) for 12 h, showed that the Cys138/141 mutation blocked H_2S-activated FXR target genes *SHP*, *MAFG*, and *BSEP* mRNA expression (Figure S17). Taken together, these data confirmed that the Cys138/141 sites are the major sulfhydration sites and regulation sites of H_2S-promoting FXR activity.

FXR sulfhydration modulated lipid and glucose metabolism, fibrosis, and inflammation-related genes

Above data demonstrate that FXR sulfhydration at Cys138/141 sites promote its transcription activity. Therefore, whether FXR sulfhydration–occupied genes take part in the pathogenesis of NAFLD was investigated.

We performed ChIP-Seq in CSE deleted hepatocytes or Cys138/141S mutation of 293-HEK cells. By clustering FXR-occupied peaks within ±3.0 kb from the center of transcription start sites, inhibiting sulfhydration (*CSE* knockout) slightly increased and removing sulfhydration (Cys138/141S mutation) mildly decreased FXR occupancy genes compared with the wild type (Figure. 8A). By cross-analysis, we identified 1374 upregulated and 700 downregulated genes in Cys139/141S mutation-enrichment genes and 212 upregulated and 189 downregulated genes in CSE knockout-enrichment genes. We then performed bulk RNA-sequencing (RNA-seq) and identified 251 Cys139/141S mutation-enrichment genes by intersection between ChIP-Seq changed and RNA-seq changed genes and 16 *CSE* knock out (KO) enriched genes (Figure 8B). GO analysis showed that these genes were enriched for fatty acid and cholesterol metabolism, insulin signaling and glucose metabolism, and immunity and inflammation and were in the fibrosis pathway (Figure 8C). Among these genes, we used integrative genomics viewer screenshots to exhibit some selected genes, cAMP responsive element binding protein 5, phosphotyrosine interaction domain containing 1, inositol 1,4,5-trisphosphate receptor type 2, secreted phosphoprotein 1, and caspase recruitment domain family member 11, and then confirmed that reducing (*CSE* KO) or removing (Cys138/141S mutation) sulfhydration FXR decreased binding to the promoter of these genes (Figure 8D). These high-output experiments confirm CSE/H_2S protection by sulfhydrating FXR, thereby attenuating hepatic lipid deposition, insulin resistance, inflammation, and liver fibrosis.

DISCUSSION

CBS and CSE are two key enzymes in the methionine trans-sulfuration pathway and function as a single system in mammalian cysteine generation and concomitant H_2S production.[22] H_2S exhibits a protective role in HFD-induced NAFLD[9,11] or a methionine-choline deficient diet that induces NASH.[23] These data infer that hepatic CSE might play an essential role in NAFLD development due to the dominant expression of CSE in liver compared to CBS.[8]

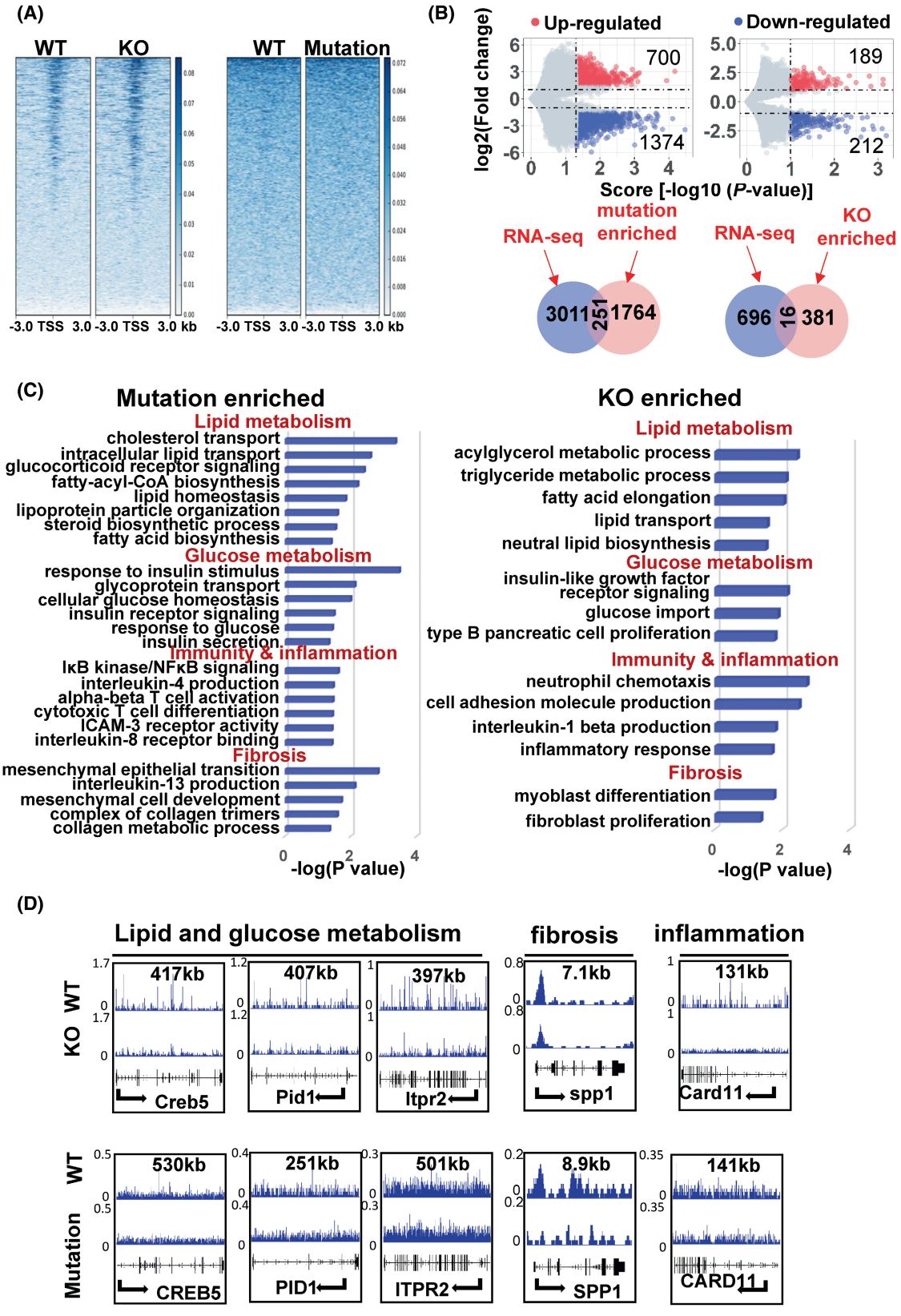
In the present study, we confirmed hepatocellular CSE expression was downregulated in patients with NAFLD, HFD-induced fatty liver mice, and OA-treated hepatocytes. Hepatocyte-specific deletion of CSE exacerbated HFD-induced lipid deposition in hepatocytes, and the affected livers were prone to NASH with fibrosis. In contrast, H_2S donor treatment attenuated these effects of decreased CSE activity. Next, we demonstrated that FXR sulfhydration in its zinc finger domain by the CSE/H_2S system effected a translational modification that promoted FXR activity. In turn, FXR activation could upregulate CSE expression,[24] and this interaction between FXR and CSE increased hepatic protection in NAFLD (Figure S18).

Many studies have addressed the effects of endogenous H_2S generation system changes in the pathogenesis of NAFLD. According to a previous study, CBS and CSE expression is upregulated in HFD-induced mice after 5 weeks exposure.[25] In contrast, in another study, it was demonstrated that CSE protein was significantly reduced in the liver of mice fed an HFD for more than 8 weeks, and this was associated with a compensatory increase in CBS protein.[9] It has also been shown that expression of another H_2S generating enzyme in the liver (3-MST) is also increased both in patients with NAFLD and in an HFD mouse model.[13] Here, we confirmed that CSE protein levels were decreased in the steatotic liver tissues in patients with NAFLD. Consistently, CSE protein expression is also downregulated in the liver tissues of mice fed an HFD for 12 weeks or in OA-treated hepatocytes. However, we did not find that CBS or 3-MST was increased either in our mouse model or in our cell model. Collectively, these data suggest that hepatic CSE expression is upregulated in the early stages of NAFLD, possibly due to compensatory changes induced by oxidative stress[25] or local inflammation with increased tumor necrosis factor-α[26] (TNFα has been shown to quickly induce CSE expression[27]). In cirrhosis phase, CSE protein was markedly decreased and was almost undetectable in the areas of fibrosis (Figure 1A).

It has been previously shown that in the *CBS* knockout mouse liver that there were enlarged multinucleated hepatocytes filled with microvesicular lipid droplets,[28] hepatic oxidative stress, perilobular mononuclear inflammatory infiltration and pericellular fibrosis,[29] and also hyperhomocysteinemia[28,29] (i.e., a noninvasive marker of NAFLD[30]). In contrast to that model, global CSE deletion did not induce any indices

FIGURE 8 Sulfhydrated farnesoid X receptor (FXR) mediated lipid and glucose metabolism, inflammation, fibrosis genes. ChIP-Seq was performed for reduced FXR sulfhydration (*CSE* knockout hepatocytes) or removed FXR sulfhydration (Cys138/141 sites mutation plasmid transfected 293-HEK cells). (A) Heat map of FXR-occupied genes based on FXR signal around FXR peak center. (B) Volcano plot shows the FXR-occupied genes with removed (mutation) or reduced (knockout) sulfhydration (upper panel), cross-analysis of the bulk RNA-sequencing data, and the overlapped genes are shown by Venn diagram. (C) Gene Ontology (GO) analysis in mutation or knockout enriched genes. (D) Visualization of ChIP-Seq results for five representative FXR sulfhydration–occupied genes (lipid and glucose correlated: cAMP responsive element binding protein 5 [*CREB5*], phosphotyrosine interaction domain containing 1 [PID1], IPTR; fibrosis correlated: secreted phosphoprotein 1 (SPP1); inflammation correlated: caspase recruitment domain family member 11 [CARD11]) by Integrative Genomics Viewer (IGV). $N = 4$.

of hepatic dysfunction and was associated with mildly elevated serum homocysteine levels and H_2S production reduction.[31] A global knockout of *CBS* and *CSE* induced methionine metabolism and caused hyperhomocysteinemia. To clarify the role of endogenous CSE in the pathogenesis of NAFLD, we used a hepatocyte-specific CSE knockout mouse (CSE^{LKO}) model, which decreased the generation ability of H_2S



by ~75% but did not increase serum homocysteine levels. Feeding these *CSE*^{LKO} mice with an HFD for 12 weeks, more severe hepatic steatosis, insulin resistance, and increased serum lipids occurred, with more marked de novo fatty acid synthesis (coinciding with H_2S donor inhibitory effects[23]). However, there were no significant increases in fatty acid uptake, oxidation, or triglyceride synthesis. More interestingly, *CSE*^{LKO} mice showed an increase in lobular inflammation infiltration and collagen deposition, suggesting a potential risk to development of NASH with fibrosis. Global *CSE* knockout mice also developed severe hepatic steatosis with higher serum cholesterol and lower serum/liver triglyceride levels, in association with LXRα downregulation.[32] Although there was a similar steatosis phenotype between the global *CSE* knockout and our model, the intestinal CSE loss may also disturb fatty acid and bile acid absorption, which may cause the differences in triglyceride levels and LXRα expression in these two mouse models. Therefore, the present study provides more precise evidence of the distinct role of the hepatocellular endogenous CSE/H_2S system in the pathogenesis of NAFLD.

FXR is an essential metabolic nuclear receptor affecting cholesterol secretion, bile acid biosynthesis, glucose, and lipid metabolism.[33] The FXR agonists OCA[34,35] and cilofexor[36] have reduced hepatic fat content in phase 2 and 3 randomized clinical trials. FXR activation affects its target genes such as SHP and FGF19 expression and modulates fatty acid de novo synthesis,[37] FAS,[38] fatty acid oxidation,[39] very low density lipoprotein secretion,[40] and triglyceride clearance (by increasing apoC-II and decreasing apoC-III, angiopoientin-like protein, to enhance LPL activity).[33] Here, by screening RNA-seq data and by enrichment analysis, we identified and confirmed that FXR levels were prone to CSE changes by genomic modification. By contrast, the effect of H_2S donor protection in NAFLD (in accord with previous studies[11,41]) was blocked by knockdown of FXR, thus indicating that the FXR pathway may be a molecular mechanism of H_2S hepatocellular protection. Due to FXR activation, H_2S lowered fatty acid de novo synthesis genes, such as *SREBP-1c*, *FAS*,[41] *ACC*, and *SCD1*, and triglyceride clearance genes, such as apoC-II upregulation and apoC-III and LPL reduction. Therefore, this study shows that CSE/H_2S system is a potential activator of FXR.

FXR activity is also mediated by post-translational modification. FXR agonist promotes FXR Ser154 phosphorylation, modulating its activity and subsequent degradation.[42] Phosphorylation at Tyr67 site increases FXR activity, contributing to bile acid synthesis.[43] Methylation at Lys 206 site increases FXR transcription activity.[44] Acetylation at Lys 217 enhances its stability but inhibits its binding activity to RXR.[45] The Lys-122 and Lys-277 sites of FXR can be SUMOylated, and Lys-277 SUMOylation regulates FXR transrepression of inflammatory gene expression.[46] Atypical SUMOylation at Lys-325, which requires prior Ser-327 phosphorylation, also contributes to FXR activity and its degradation.[47] Here, we have identified a post-translational modification: sulfhydration of FXR at Cys138/141 sites. This post-translational modification promotes FXR binding to Zn^{2+}, FXR nuclear translocation, and target genes transcription. Therefore, we propose that sulfhydration of FXR is a post-translation of FXR, affecting its transcriptional activity.

Bile acid receptors G protein-coupled bile acid receptor 1 (GPBAR1, also known as TGR5),[48] and FXR activation increase CSE expression/activity and H_2S production.[24] Experimental evidence also demonstrates that CSE is a target gene of FXR.[24] Here, our data show that CSE/H_2S may sulfhydrate FXR at a Zn^{2+} binding domain and promote its transcriptional ability. More intriguingly, ChIP-Seq association with RNA-seq cross-analysis showed that FXR sulfhydration was associated with changes in genes affecting lipid metabolism, inflammation, fibrosis, and glucose metabolic regulation. Thus, hepatic CSE/H_2S and FXR interaction highlights a "positive feedback mechanism" affecting bile acid metabolism, hepatic steatosis, and fibrosis.

Both clinical trials and animal experiments demonstrated that FXR agonist, such as OCA or some small molecular chemicals, effectively reduced NAFLD but increased potential risk of pruritus or cardiovascular diseases (serum cholesterol elevation). H_2S per se exerts anti-inflammation, anti-fibrosis, and immunoregulatory effects and also lowered serum cholesterol and anti-atherosclerosis. Furthermore, H_2S enhanced FXR activity, then heightened CSE/H_2S by "positive feedback" regulation, to compensate for CSE/H_2S system reduction in NAFLD. Thus, FXR agonist combination with H_2S donor or FXR agonist-derived H_2S donors to treat NAFLD, where one may reduce the FXR agonist dose and the other H_2S per se has cardiovascular protection effects, could be effective to attenuate NAFLD or NASH, avoiding side effects of FXR agonists in the meantime.

AUTHOR CONTRIBUTIONS

Bin Geng and Jun Cai conceived the idea and designed the experiments. Yu han and Liangjie Tang collected patient's sample and clinical data. Liming Yang contributed to the CSE conditional knockout mice construction. Wengjing Xu, Changting Cui, Zhenzhen Chen, and Haizeng Zheng performed experiments. Chunmei Cui and Qinghua Cui performed the bioinformatic analysis. Ming-Hua Zheng, Jianglin Fan, and Guoheng Xu analyzed the data and improved the manuscript. Christopher D. Byrne and Giovanni Targher critically reviewed the data and contributed to writing the manuscript.

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CONFLICT OF INTEREST

Nothing to report.

ETHICAL APPROVAL

The study protocol conforms to the ethical guidelines of the 1975 Declaration of Helsinki as reflected in a priori approval by the ethics committees of the First Affiliated Hospital of Wenzhou Medical University (NO. 2016-0246).

DATA AVAILABILITY STATEMENT

The data, analytical methods and some animal materials will be made available on request to other researchers for reproducing the results or replicating the procedure. Requests for data should be made to the corresponding author.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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