Direct AMPK Activation Corrects NASH in Rodents Through Metabolic Effects and Direct Action on Inflammation and Fibrogenesis

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No approved therapies are available for nonalcoholic steatohepatitis (NASH). Adenosine monophosphate–activated protein kinase (AMPK) is a central regulator of cell metabolism; its activation has been suggested as a therapeutic approach to NASH. Here we aimed to fully characterize the potential for direct AMPK activation in preclinical models and to determine mechanisms that could contribute to efficacy for this disease. A novel small-molecule direct AMPK activator, PXL770, was used. Enzyme activity was measured with recombinant complexes. *De novo* lipogenesis (DNL) was quantitated *in vivo* and in mouse and human primary hepatocytes. Metabolic efficacy was assessed in *ob/ob* and high-fat diet–fed mice. Liver histology, biochemical measures, and immune cell profiling were assessed in diet-induced NASH mice. Direct effects on inflammation and fibrogenesis were assessed using primary mouse and human hepatic stellate cells, mouse adipose tissue explants, and human immune cells. PXL770 directly activated AMPK *in vitro* and reduced DNL in primary hepatocytes. In rodent models with metabolic syndrome, PXL770 improved glycemia, dyslipidemia, and insulin resistance. In mice with NASH, PXL770 reduced hepatic steatosis, ballooning, inflammation, and fibrogenesis. PXL770 exhibited direct inhibitory effects on pro-inflammatory cytokine production and activation of primary hepatic stellate cells. *Conclusion:* In rodent models, direct activation of AMPK is sufficient to produce improvements in all core components of NASH and to ameliorate related hyperglycemia, dyslipidemia, and systemic inflammation. Novel properties of direct AMPK activation were also unveiled: improved insulin resistance and direct suppression of inflammation and fibrogenesis. Given effects also documented in human cells (reduced DNL, suppression of inflammation and stellate cell activation), these studies support the potential for direct AMPK activation to effectively treat patients with NASH. (*Hepatology Communications* 2022;6:101-119).

Nonalcoholic fatty liver disease (NAFLD) is the most common hepatic disorder worldwide. Overnutrition and a sedentary lifestyle are principal causes; however, onset and progression are influenced by other factors such as genetics and comorbid conditions.[1]

Abbreviations: ADaM, allosteric drug and metabolite; AMPK, AMP-activated protein kinase; ANOVA, analysis of variance; CBM, carbohydrate-binding module; DC, dendritic cell; DIO-NASH, diet-induced obesity–NASH; DNL, de novo lipogenesis; FFA, free fatty acid; GPR, glucose production rate; HbA1C, hemoglobin A1c; HFD, high-fat diet; HSC, hepatic stellate cell; HSL, hormone-sensitive lipase; IHC, immunohistochemistry; IL, interleukin; LPS, lipopolysaccharide; MAFLD, metabolic dysfunction–associated fatty liver disease; MCP1, monocyte chemoattractant protein 1; moDC, monocyte-differentiated dendritic cell; moMac, monocyte-differentiated macrophage; NAFLD, nonalcoholic fatty liver disease; NASH, nonalcoholic steatohepatitis; NF-κB, nuclear factor kappa B; SSGIR, steady-state glucose infusion rate; T2DM, type 2 diabetes mellitus; TG, triglycerides; TGF-β, transforming growth factor β; TNF-α, tumor necrosis factor α; α-SMA, smooth muscle actin.

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Approximately 10%-30% of patients with NAFLD progress to nonalcoholic steatohepatitis (NASH), manifested by the presence of lobular inflammation, hepatocellular damage, and fibrosis; NASH can lead to liver failure and hepatocellular carcinoma.[1]

Importantly, NAFLD/NASH are associated with multiple comorbidities. Type 2 diabetes mellitus (T2DM) has the strongest overlap; 20%-30% of patients with T2DM have NASH, and up to 47% of patients with NASH also have T2DM.[2,3] Furthermore, pathways contributing to their pathophysiology are highly convergent.[4] The importance of metabolic dysfunction in NAFLD pathophysiology was highlighted by experts who suggested new nomenclature: redefining NAFLD as metabolic dysfunction–associated fatty liver disease or MAFLD.[1,5]

Increased free fatty acid (FFA) flux from adipose tissue lipolysis along with an increase in *de novo* lipogenesis (DNL) in hepatocytes are major contributors to steatosis.[6] Insulin resistance is a driver of this pathophysiology through impaired inhibition of lipolysis[7] and stimulation of DNL from hyperinsulinemia.[8] Insulin resistance, dyslipidemia, and peripheral adipose tissue dysfunction also contribute to a systemic proinflammatory state, a major cause of the progression to NASH.[6]

AMP-activated protein kinase (AMPK) is a heterotrimeric enzyme complex consisting of catalytic α (α1 and α2), regulatory β (β1 and β2), and γ (γ1, γ2, and γ3) subunits that controls key metabolic pathways involved in the development of NASH.[9] AMPK activity is tightly regulated by posttranslational modifications and allosteric effects mediated through multiple domains and interactions, including the carbohydrate-binding module (CBM) and the allosteric drug and metabolite (ADaM) site. Recently, a class of direct pharmacological AMPK activators has been shown to bind through the ADaM site.[10,11] In the liver, AMPK inhibits DNL and increases fatty acid oxidation, and its activation has been shown to reduce steatosis.[12] Interestingly, AMPK activation has been implicated as a means of inhibiting lipolysis in adipocytes.[13] However, this potential effect is controversial.[14] In adipose tissue macrophages, AMPK inhibits multiple pro-inflammatory signaling pathways, including interleukin (IL)-1β and tumor necrosis factor α (TNF-α), and its activation has been proposed to limit liver inflammation.[15,16] AMPK activation has also been suggested as an approach to attenuate hepatic fibrogenesis by inhibiting primary inflammatory injury, extracellular matrix secretion, and the induction of hepatic stellate cells (HSCs).[17-20]

Taken together, these elements point toward AMPK activation as an attractive approach to therapeutics targeting MAFLD/NAFLD and NASH. Consistent with this concept, constitutively active AMPK[21,22] or small-molecule direct AMPK activators A769662,[12,23] C13,[24] PF-249/739,[25] PF-06409577,[26] and Compound 1[27] have been shown to decrease liver fat content in rodents.

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Despite extensive efforts, there are still no approved therapies for NASH. PXL770 is an orally bioavailable thienopyridone small molecule that is currently in clinical development for NASH treatment (ClinTrials.gov; NCT03763877); it is also the first direct AMPK activator that is advanced into human efficacy studies. PXL770 was discovered through chemical optimization of one initial lead compound identified during a classical discovery high-throughput screening process performed using a recombinant AMPK isoform (α2β1γ1). Physical chemistry, pharmacokinetics, and efficacy properties were part of the criteria for the chemical optimization. Here, we show that PXL770 directly increases AMPK activity by both allosteric activation and protection from dephosphorylation. We confirmed the benefit of direct AMPK activation to improve glucose metabolism and dyslipidemia in rodent models of metabolic syndrome, and to reduce hepatic DNL *in vitro* and *in vivo*. Using euglycemic hyperinsulinemic clamp methods, we showed for the first time that direct AMPK activation enhances insulin sensitivity *in vivo*. In a diet-induced (DIO) mouse NASH model, we showed that direct AMPK activation ameliorated each of the classical NASH hallmarks, including steatosis, ballooning, inflammation, and fibrogenesis. Importantly, we unveiled that direct AMPK activation can produce independent direct effects in human cells to reduce DNL (hepatocytes), suppress inflammation (macrophages and dendritic cells [DCs]), and inhibit stellate cell activation. Thus, results obtained with PXL770 provide evidence for new attributes linked to direct AMPK activation and suggest the potential for translation to humans, supporting prospects in the treatment of NASH and NASH-related comorbidities.

Materials and Methods

All procedures were performed in accordance with the principles and guidelines established by the European Convention for the Protection of Vertebrate Animals Used for Experimental and Other Scientific Purposes (Council of Europe, ETS 123; 1991).

IN VITRO ASSAYS
DIRECT AMPK ASSAYS

For direct AMPK activation, recombinant AMPK isoforms were obtained from Sino Biological (Beijing, China), 2B Scientific (Oxfordshire, United Kingdom), and SignalChem Lifesciences Corp. (Richmond, BC). AMPK activity was measured using Delfia Fluorescent–based technology (PerkinElmer, Waltham, MA) as described in the Supporting Information. To assess the interaction with CBM domain, wild-type AMPK (α1β1γ1) or AMPK harboring a deletion or mutation was incubated in the presence or absence of recombinant PP2C, and AMPK activity was measured as described previously.

LIPOGENESIS MEASUREMENT IN PRIMARY HUMAN AND MOUSE HEPATOCYTES

Primary mouse hepatocytes were prepared from C57BL/6J mice (Harlan, Houston, TX), and primary human hepatocytes were purchased from Biopredic International (Ref. #HEP200B0; Saint Grégoire, France), both cultured as described in the Supporting Information. Effects of PXL770 on basal and insulin-stimulated lipogenesis were determined by measuring incorporation of [1-^{14}C]-acetate into total lipids as described in the Supporting Information.

INTRACELLULAR TRIGLYCERIDE CONTENT DETERMINATION IN CONTROL OR AMPKα1α2-NULL HEPATOCYTES

AMPKα1α2-null mice were obtained as described in the Supporting Information. Hepatocytes were incubated in a medium containing 25 mM glucose with 100 nM insulin (lipogenic condition), with indicated concentrations of PXL770, and triglyceride (TG) content was assayed using a commercial kit (Diasys, Waterbury, CT).

ASSESSMENT OF INFLAMMATION IN *ob/ob* MOUSE ADIPOSE TISSUE EXPLANTS

Epidydimal fat pads from *ob/ob* mice were excised and treated with IL-1β or lipopolysaccharide (LPS) in the absence or the presence of 50 μM PXL770. Nuclear factor kappa B (NF-κB) activity was assessed using a commercial kit from Abcam (Cambridge, United Kingdom). IL-6 and IL-1β concentrations in cell culture supernatants were determined using commercial kits (R&D Systems, Minneapolis, MN). Details are described in the Supporting Information.

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HUMAN MACROPHAGE AND DC ASSAYS

Human CD14$^+$ monocytes were isolated from healthy volunteers and differentiated toward either macrophages (monocyte-differentiated macrophages, moMacs) or dendritic cells, DCs (monocyte-differentiated DCs, moDCs), as described in the Supporting Information. Polarized moMacs were exposed to PXL770 as also described in the Supporting Information. moDCs were stimulated and exposed to PXL770 followed by phenotypic profiling, as described in the Supporting Information. All of the results were expressed as a percentage of vehicle-control treated cells.

IN VITRO HSC ASSAYS

Primary HSCs were obtained from human donors and C57Bl6 mice (Supporting Information). HSCs were activated with transforming growth factor β (TGF-β) alone and exposed to PXL770 or LY-364947, a selective inhibitor of TGF-β type 1 receptor. Phenotyping of HSCs to quantitate pathways relating to fibrogenesis and AMPK target engagement was performed using gene-expression measurements, western blotting, and an assessment of DNL. All methods are described in the Supporting Information.

In Vivo Studies

HEPATIC LIPOGENESIS MEASUREMENT IN C57BL/6J MICE

Mice were fasted (24 hours) and refed (12 hours) and treated with PXL770 35 mg/kg or 75 mg/kg. The rate of hepatic lipid synthesis was quantified by determining the rate of incorporation of ^3H_2O into lipids by liquid scintillation counting. Details are described in the Supporting Information. Twice daily (bid) dosing was used in all *in vivo* studies to ensure 24-hour coverage, given an estimated terminal $t_{1/2}$ of 8.9 hours (data not shown).

ob/ob MOUSE MODEL

ob/ob mice were treated by oral gavage for 5 days or 5 weeks with 75 mg/kg or 25 and 50 mg/kg of PXL770 twice daily, respectively. After 5 days of treatment, an oral glucose tolerance test was performed and plasma glucose, and insulin levels were measured at indicated timepoints. After 5 weeks of treatment, hemoglobin A1c (HbA1C) and plasma TG, FFAs, and glycerol were measured (details in Supporting Information).

EUGLYCEMIC HYPERINSULINEMIC CLAMP

After 10 weeks of exposure to a high-fat diet (HFD; ssniff Spezialdiaten, Soest, Germany; 60% of energy from fat), mice were treated with vehicle (control HFD), PXL770 75 mg/kg twice daily, or pioglitazone 25 mg/kg once daily for 6 weeks. Standard diet (SD) mice were treated with vehicle. A euglycemic hyperinsulinemic clamp with glucose production/turnover measurements was then performed in fasted mice as described in the Supporting Information.

DIO-NASH MOUSE MODEL

The diet-induced obesity (DIO)–NASH mouse model[28,29] was established as described in the Supporting Information.

Mice were fed with a diet high in fat for 41 weeks before starting the treatment with 35 mg/kg or 75 mg/kg PXL770 for 8 weeks. At the end of treatment, blood glucose levels (EKF Diagnostics, Cardiff, United Kingdom), plasma alanine aminotransferase (ALT), aspartate aminotransferase (AST), TG, and total cholesterol were measured using commercial kits (Roche Diagnostics, Basel, Switzerland). Plasma FFAs were determined using a commercial kit (WACO Chemicals, Richmond, VA).

Terminal liver samples were analyzed for TG content (Roche Diagnostics). Liver histology (hematoxylin and eosin and sirius red staining) and measurements of specific protein levels (immunohistochemistry [IHC]) were performed as described in the Supporting Information. The expression level of specific genes was assessed through RNA sequencing using RNA extracts from terminal liver samples.[28,29] Flow cytometry was used for measurements of selected immune cells present in liver tissue, as described in the Supporting Information.

STATISTICAL ANALYSIS

Results are expressed as means ± SEM. Groups were compared in unpaired two-tailed Student *t* tests

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or one-way analysis of variance ANOVA (or Kruskal Wallis test) with Dunnett's *post hoc* test for multiple comparisons, where appropriate. Differences between groups were considered statistically significant if $P < 0.05$. IC50s were calculated by nonlinear regression analysis and correlations by simple linear regression. GraphPad Prism 8.0 software was used.

Results

PXL770 IS A DIRECT AMPK ACTIVATOR

The small molecule PXL770 (Fig. 1A) directly activated recombinant AMPK heterotrimeric proteins, allosterically and/or by protecting AMPK from dephosphorylation induced by PP2C (Table 1). In general, higher potency for AMPK complexes that contain the β1 subunit was clearly evident (Table 1). Similar potency was observed whether the catalytic subunit was α1 versus α2. Potential off-target activity was excluded by screening against a panel of 56 receptors, ion channels, and transporters (Eurofins Cerep, Celle-Lévescault, France); only one target showed a possible effect. In an assay of CCK1 receptor binding, modest inhibition was noted (data not shown).

ACTIVATION BY PXL770 REQUIRES AN INTACT ADaM BINDING SITE WITHIN AMPK

PXL770's effect to protect AMPK from dephosphorylation was abolished by mutation of S108 within the CBM of β1 to an alanine (Fig. 1B). This result is consistent with that reported with another AMPK activator (A769662).[30] We also found that deletion of the N-terminal 185 residues of β1, which includes the CBM, abolished protection by PXL770. In contrast, deletion of the N-terminal 76 residues of β1, which

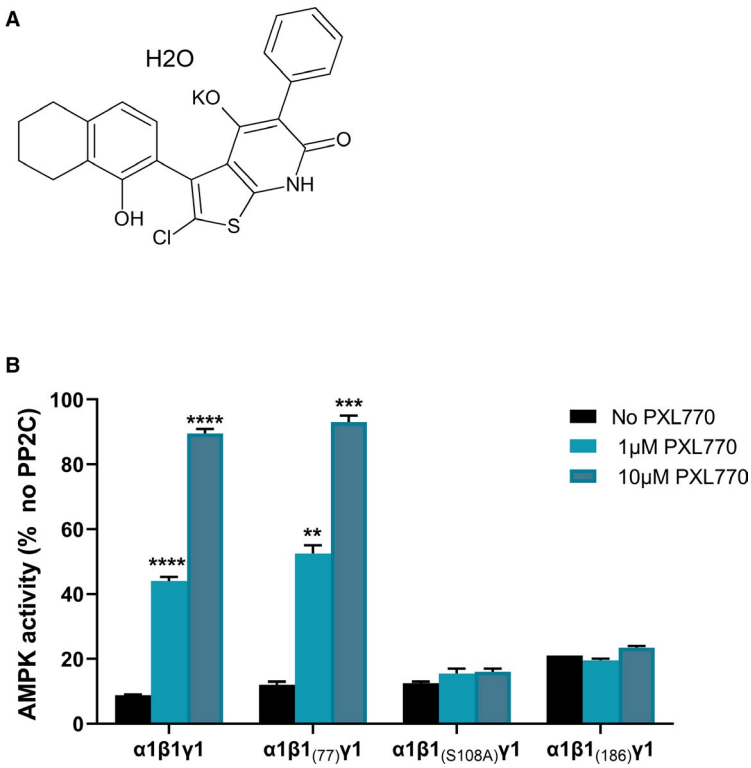

FIG. 1. PXL770 activates AMPK. (A) Chemical structure of PXL770 monohydrate potassium salt. (B) Effect of mutations within β1 on protection against dephosphorylation: Wild-type AMPK (α1β1γ1) or AMPK harboring deletion of the N-terminal 76 ($\alpha1\beta1_{(77)}\gamma1$) or N-terminal 185 ($\alpha1\beta1_{(186)}\gamma1$) residues of β1, or a point mutation of S108A in β1 ($\alpha1\beta1_{[S108A]}\gamma1$). PXL770 had no effect with mutations in β1 N-terminal 185 or S108A. $^{**}P < 0.01$, $^{***}P < 0.001$, and $^{****}P < 0.0001$ versus no PXL770 (one-way ANOVA); n = 2-4 replicates/condition.

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TABLE 1. *IN VITRO* ACTIVITY OF PXL770 ON RECOMBINANT AMPK HETEROTRIMERIC PROTEINS

	AMPK Activity	
Heterotrimerics AMPK	EC50	Emax %
α1β1γ1	16.2 nM	155
α1β1γ2	42.1 nM	200
α1β1γ3	64 nM	450
α2β1γ1	1,338 nM	240
α2β1γ2	68.7 nM	700
α2β1γ3	41.5 nM	550
α1β2γ1	1.3μM	115
α1β2γ3	>μM	130
α2β2γ1	>μM	>500
α2β2γ2	>μM	820
α2β2γ3	>μM	210

Note: Emax, the maximal stimulation achieved from basal activity, is expressed as a percentage of basal activity.

leaves the CBM intact, does not alter this effect of PXL770. We further observed that PXL770 does not bind competitively to nucleotide binding sites 1 or 3 of the γ-subunit (data not shown). Collectively, these data are consistent with an allosteric mechanism for activation mediated by binding to the AdaM site.

PXL770 IMPROVES GLYCEMIA AND INSULIN SENSITIVITY IN RODENTS WITH METABOLIC SYNDROME

In *ob/ob* mice, short-term treatment with PXL770 75 mg/kg (5-day) improved glucose tolerance (Fig. 2A); no effect on body weight was observed (data not shown). Given the lack of an increase in insulinemia (Fig. 2A), an improvement of insulin sensitivity was suggested. Five weeks of treatment with PXL770 50 mg/kg decreased HbA1c (Fig. 2B) and plasma TG, plasma FFA, and plasma glycerol levels (Fig. 2B).

To definitively assess whether PXL770 could enhance insulin sensitivity, a euglycemic hyperinsulinemic clamp was performed in HFD mice. After 6 weeks of treatment, insulin sensitivity was increased in PXL770-treated mice compared with vehicle-treated mice (Fig. 2C, Supporting Table S1). The steady-state glucose infusion rate (SSGIR) increased, and a strong decrease in (hepatic) glucose production rate (GPR) in response to insulin infusion was observed (Fig. 2C). As expected, pioglitazone (used as an insulin sensitizer reference) increased SSGIR without any effect on GPR (Fig. 2C, Supporting Table S1). Interestingly, the SSGIR in both PXL770 and pioglitazone groups was normalized, reaching the level measured in SD mice.

PXL770 REDUCES DNL IN PRIMARY MOUSE AND HUMAN HEPATOCYTES AND *IN VIVO*

DNL is a key pathway contributing to steatosis,[31] and AMPK is known to inhibit DNL.[32] In isolated primary mouse and human hepatocytes, treatment with PXL770 induced dose-dependent inhibition of DNL (Fig. 3A). Importantly, similar potency of PXL770 was evident in both mouse and human primary hepatocytes with IC_{50} values of 2.8 μM and 2.6 μM, respectively (Fig. 3A).

The effect of PXL770 was also assessed in insulin-stimulated human hepatocytes. In this context, PXL770 decreased lipid synthesis by 70%-90% (Fig. 3B), in line with dose-dependent increases in ACC S79/221 phosphorylation and AMPKα Thr172 phosphorylation (Supporting Fig. S1). In these experiments, we also confirmed that PXL770 did not impede the activation of insulin signaling as measured by Akt phosphorylation (Supporting Fig. S1).

To examine the requirement of AMPK for PXL770's inhibitory effects, DNL studies were conducted using AMPKα1α2-null hepatocytes. Treatment with PXL770 decreased intracellular TG accumulation in control hepatocytes, whereas this effect was severely blunted in AMPKα1α2-null hepatocytes (Fig. 3C).

To determine whether oral dosing with PXL770 could suppress liver $[^3H]$-H_2O incorporation into lipids, *in vivo* DNL was assessed during refeeding stimulation in mice. As expected, a strong (15-fold) induction of DNL was observed in refed vehicle-treated animals, and PXL770 treatment inhibited DNL at both doses studied (Fig. 3D).

PXL770 IMPROVES HALLMARKS OF LIVER PATHOLOGY IN A RODENT NASH MODEL

To test the hypothesis that metabolic effects of PXL770 might affect NASH, several experiments

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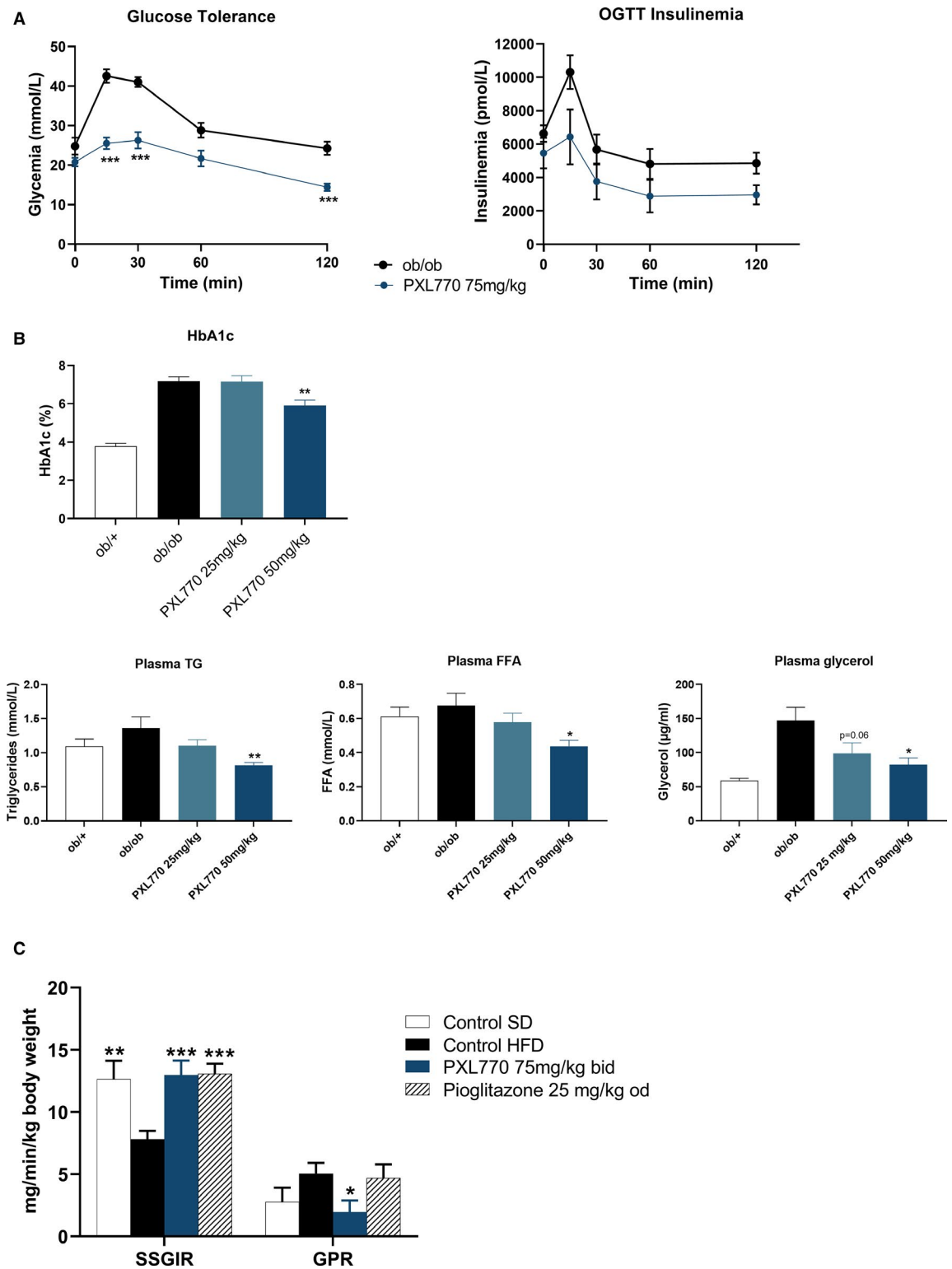

FIG. 2. Metabolic profile of PXL770 *ob/ob* mice. (A) Oral glucose tolerance test with glucose and insulin levels, after 5 days of treatment. (B) HbA1C and plasma TGs, FFAs, and glycerol after 5 weeks of treatment. $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$ versus vehicle-treated *ob/ob* mice (Kruskal-Wallis); n = 9-12 /group. (C) Measure of insulin sensitivity in HFD mice: Both SSGIR and GPR rates are shown; $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$ versus control HFD (one-way ANOVA); n = 8-21/group. Abbreviation: OGTT, oral glucose tolerance test.

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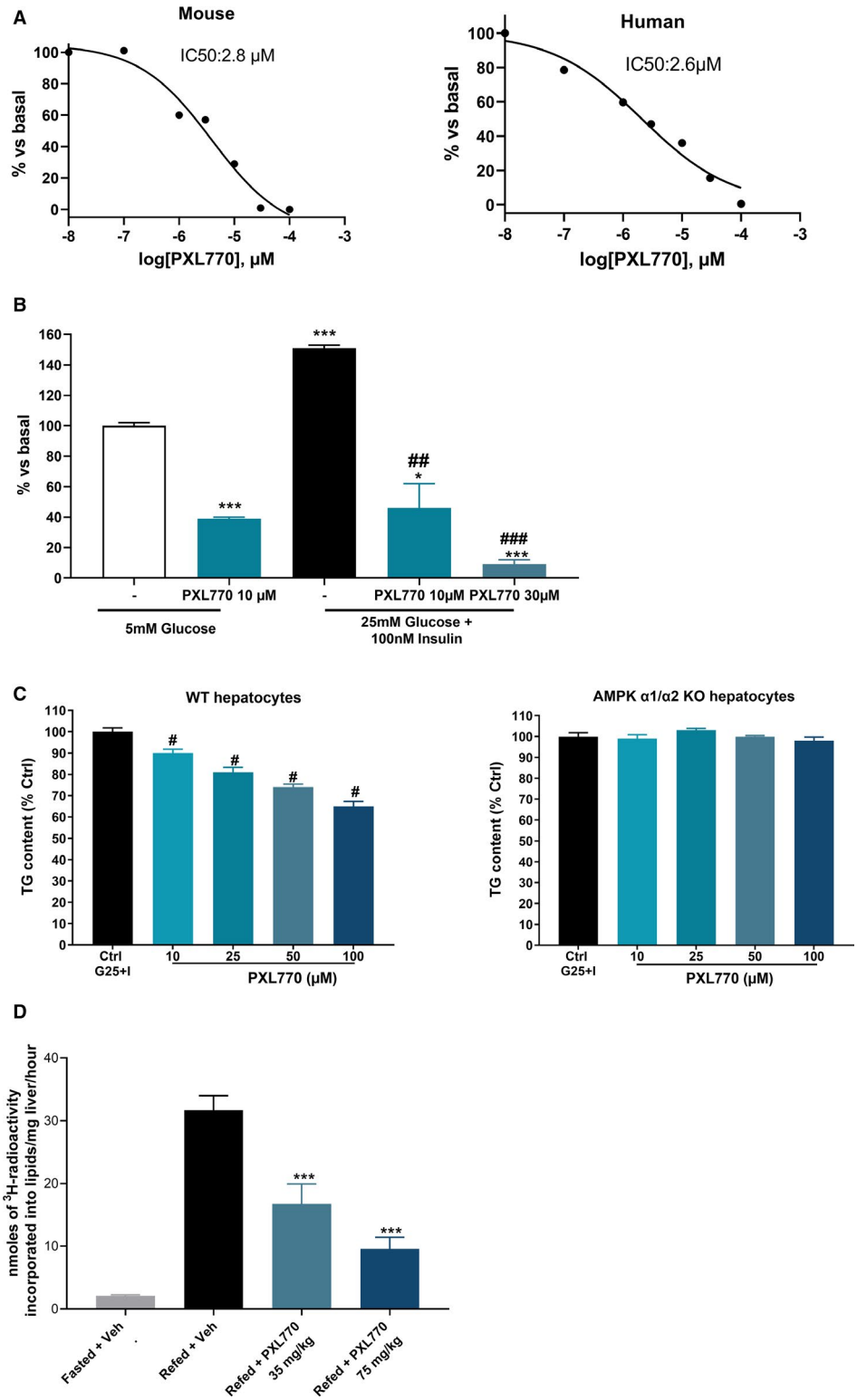

FIG. 3. Effects of PXL770 on DNL. (A) Basal DNL in mouse and human hepatocytes; n = 3 replicates. (B) Insulin-stimulated DNL in human hepatocytes; $^{*}P < 0.05$ and $^{***}P < 0.001$ versus glucose alone, and $^{\#\#}P < 0.01$ and $^{\#\#\#}P < 0.001$ versus glucose plus insulin (one-way ANOVA); n = 3 replicates. (C) TG content in wild-type and AMPK knockout mouse hepatocytes; $^{\#}P < 0.05$ versus control (one-way ANOVA); n = 3 replicates. (D) *In vivo* DNL in fasted/refeeding C57/BL6J mice; $^{\#\#\#}P < 0.001$ versus fasted $^{***}P < 0.001$ versus refed (Student *t* test, one-way ANOVA); n = 5 fasted mice, n = 10 refed mice/group.

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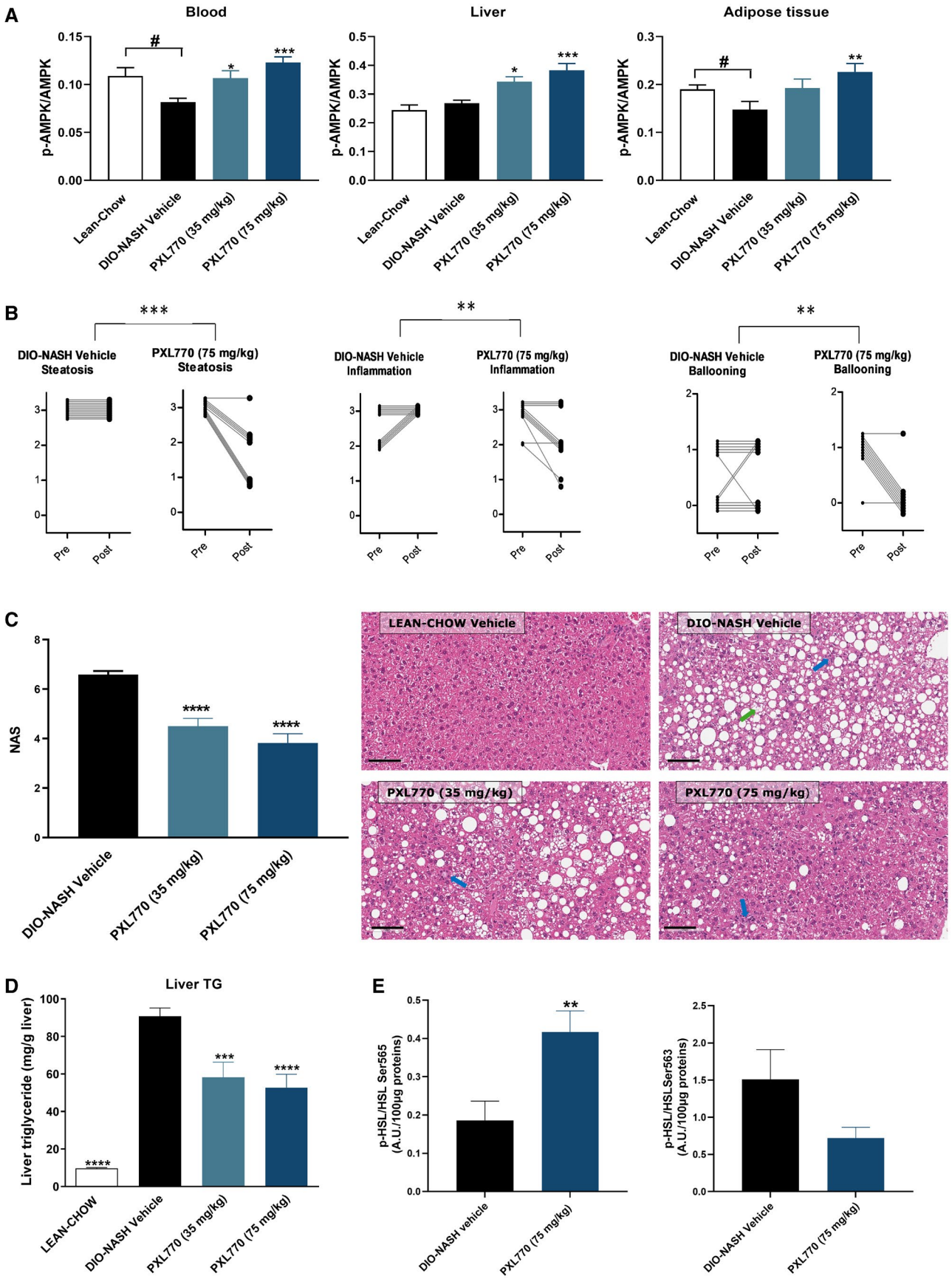

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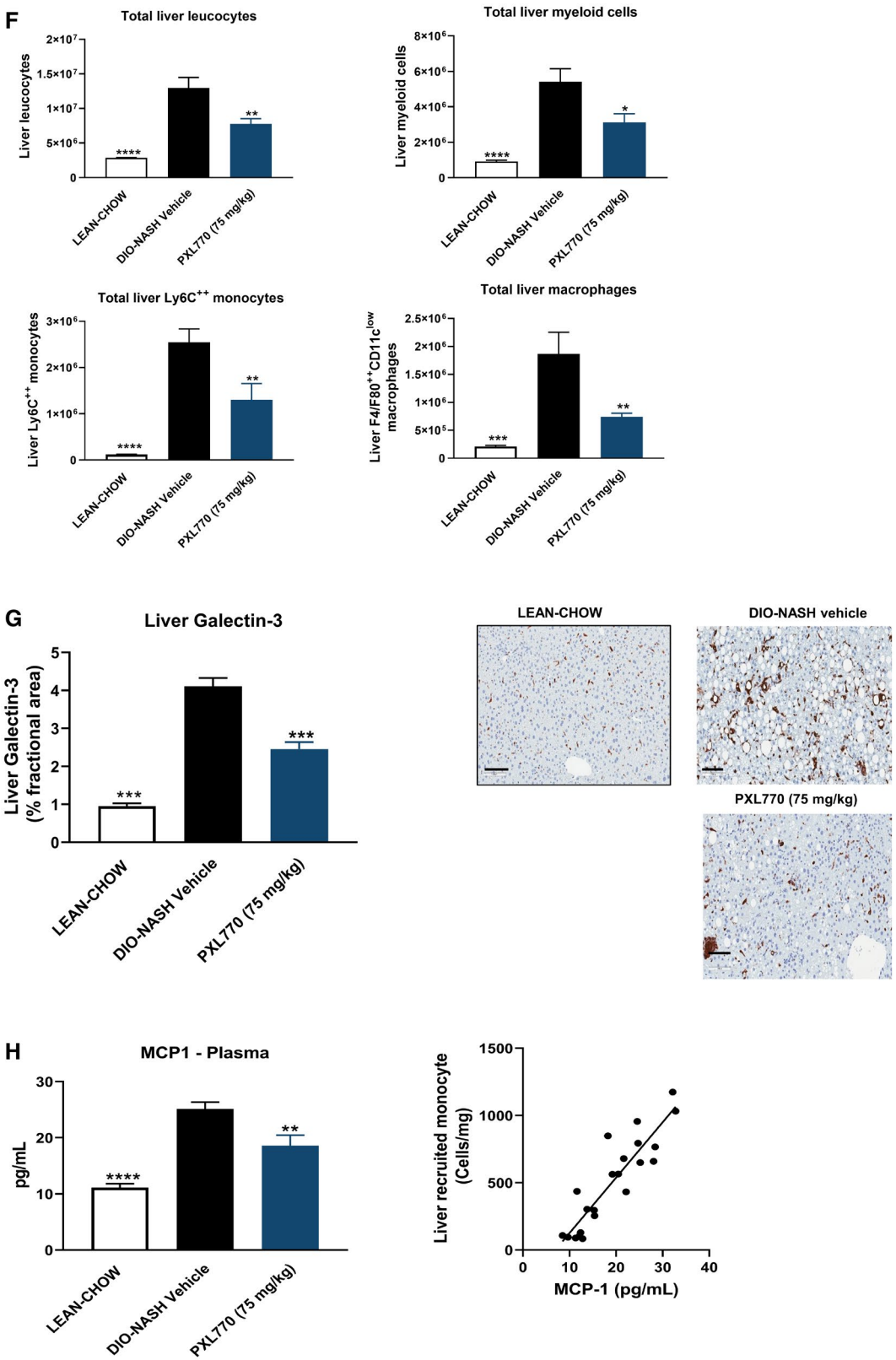

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FIG. 4. PXL770 improves steatohepatitis in DIO-NASH mice. (A) AMPK phosphorylation in blood, liver, and adipose tissue measured by enzyme-linked immunosorbent assay; $^{\#}P < 0.05$ versus vehicle (Student *t* test) (B) Liver steatosis, inflammation, and hepatocellular ballooning scores before (pre) and after (post) PXL770 treatment for each mouse. $^{**}P < 0.01$, differences in progression of prescores to postscores between vehicle-treated and PXL770-treated groups (Fisher's exact test). (C) NASH activity score; representative images of liver hematoxylin and eosin staining (magnification, ×20; scale bar, 100 μm); blue arrows, inflammatory foci; green arrow, ballooning degeneration. (D) Liver triglyceride content. (E) p-HSL/HSLSer565/563 levels in adipose tissue. (F) Liver inflammatory cell counts assessed by flow cytometry. (G) Quantitation of relative galectin-3 levels; representative images of liver galectin-3 IHC (magnification, ×20; scale bar, 100 μm). (H) Plasma MCP1 and correlation with total liver LyC^{++} monocytes. $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$, and $^{****}P < 0.0001$ versus vehicle (one-way ANOVA, Student *t* test); n = 11-12/group.

were conducted using a relevant and validated model: the amylin liver NASH (AMLN) DIO-NASH mouse.[28,29] After 8 weeks of treatment, PXL770 dose-dependently increased AMPK activation in liver, adipose tissue, and whole blood (Fig. 4A). Interestingly, compared with lean chow-fed mice, vehicle-treated DIO-NASH mice exhibited lower basal AMPK activity (pAMPK) in both epididymal adipose tissue (–22%) and in blood (–17%); however, no change in liver was evident (Fig. 4A). These findings are consistent with the concept of reduced endogenous AMPK tone that occurs in the context of overnutrition, systemic metabolic dysfunction, and inflammation.[33,34]

Vehicle-treated DIO-NASH mice demonstrated substantial liver steatosis and inflammation scores (Fig. 4B). PXL770, at both doses, reduced liver steatosis, liver inflammation, and hepatocellular ballooning scores (Fig. 4B, Supporting Fig. S2), leading to a reduction of the NASH score (NAS, Fig. 4C). The decrease in liver steatosis was also confirmed by a decrease in liver TG content (Fig. 4D).

These effects of PXL770 were also associated with substantial improvements in liver injury markers: plasma ALT and AST levels (Supporting Table S2). PXL770 also reduced liver weight (Supporting Table S2). Consistent with results in *ob/ob* mice, plasma FFA levels were also decreased by PXL770 (Supporting Table S2). To explore whether lipolysis could be inhibited, *ex vivo* adipose hormone-sensitive lipase (HSL) phosphorylation was monitored and shown to be modulated by PXL770 in this NASH model: A clear reciprocal increase in Ser565 phosphorylation versus decreased Ser563 phosphorylation was evident (Fig. 4E). Interestingly, this effect was also observed *in vitro* in isolated human and mouse adipocytes. PXL770 significantly increased HSL phosphorylation at Ser565 in both species (Supporting Fig. S3A,B). HSL phosphorylation at Ser563 tended to be modestly suppressed in human adipocytes (Supporting Fig. S3A).

PXL770 REDUCES LIVER AND ADIPOSE TISSUE INFLAMMATION IN DIO-NASH MICE

Resident liver macrophages and freshly recruited monocyte-derived macrophages have a key role in driving inflammation and fibrogenesis in NASH.[35] We therefore used flow cytometry to assess specific effects of PXL770 on immune cells and mediators of inflammation in the liver. Compared with healthy mice, DIO-NASH mice exhibited an increase in total liver leucocytes (Fig. 4F). In response to PXL770 treatment, total liver leucocytes were reduced, including reductions in total liver monocytes and resident macrophages (Fig. 4F). Consistent with these findings, PXL770 decreased levels of galectin-3 (Fig. 4G) and CD68, a pan-macrophage marker (Supporting Fig. S4), as well as reduced monocyte chemoattractant protein 1 (MCP1) gene expression (Supporting Fig. S4). Importantly, plasma MCP1 was also suppressed (Fig. 4H), and a strong correlation between plasma MCP1 levels and total liver monocytes was established (Fig. 4H). In adipose tissue of DIO-NASH mice, PXL770 decreased MCP1 gene expression without modifying markers of macrophages (CD68) or (CD163) (Supporting Fig. S4).

PXL770 DIRECTLY SUPPRESSES MARKERS OF INFLAMMATION IN *ob/ob* MOUSE ADIPOSE TISSUE EXPLANTS

Having seen *in vivo* benefits of PXL770 on adipose inflammation in DIO-NASH mice, we assessed the potential for direct anti-inflammatory effects. In explants of *ob/ob* epididymal adipose tissue, incubation

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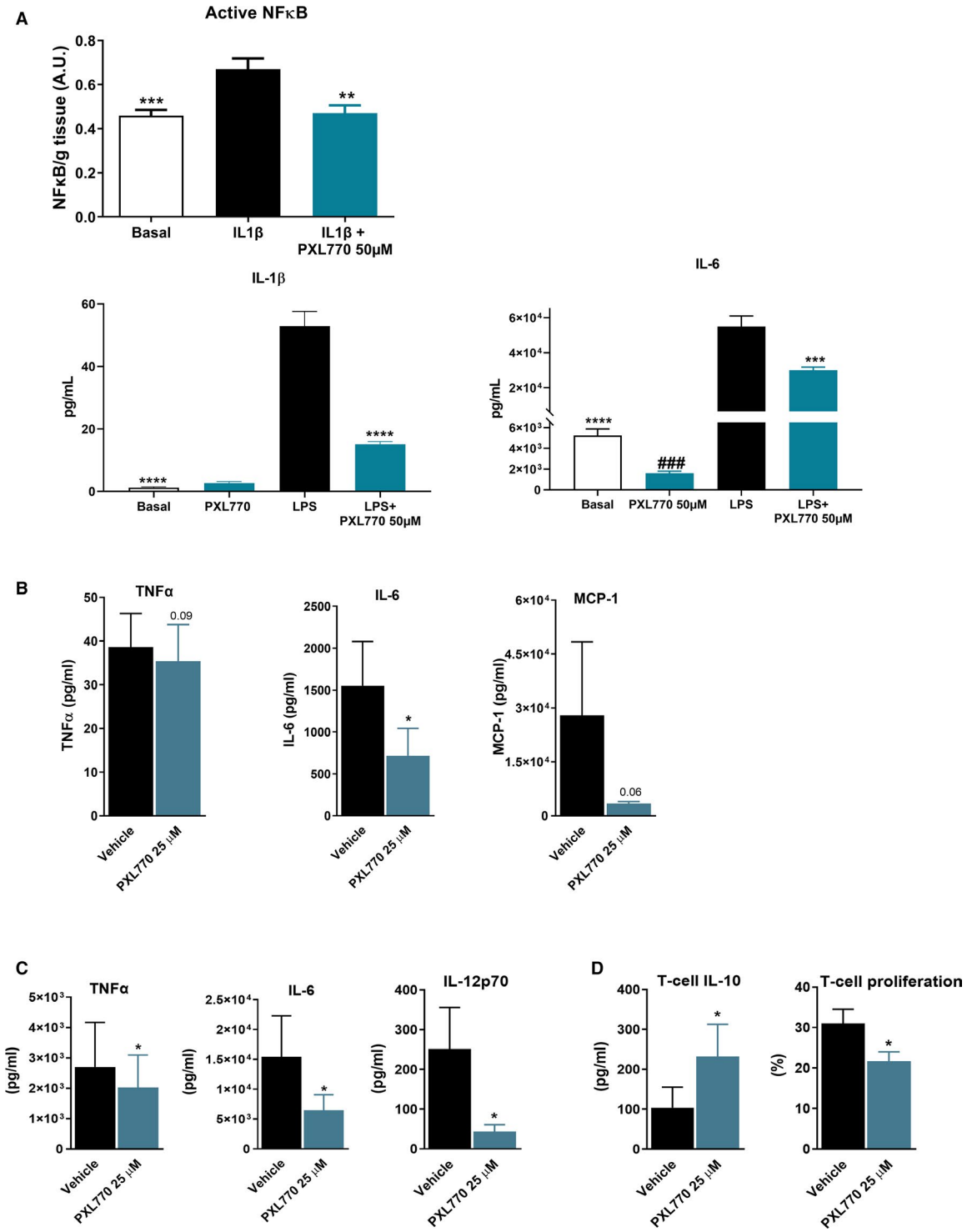

FIG. 5. PXL770 exerts direct anti-inflammatory effects. (A) *ob/ob* mice epididymal adipose tissue explants: active nuclear NF-kB activity measured (enzyme-linked immunosorbent assay) in tissue and cytokine levels in supernatants; ###$P < 0.001$ versus basal, *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$ versus IL-1β or LPS alone (Student *t* test, one-way ANOVA/Mann-Whitney U test); n = 10-11 observations, n = 7 mice. (B) Cytokine production from human M1 macrophages; n = 5 donors; nonsignificant *P* value noted for TNF-α and MCP1. (C) Cytokine production from LPS-primed human DCs (moDCs; n = 5 donors). (D) Induction of IL-10-producing T cells by LPS-primed moDCs and T-cell proliferation assay (n = 3 donors); *$P < 0.05$ versus vehicle (Student *t* test) for (B), (C), and (D).

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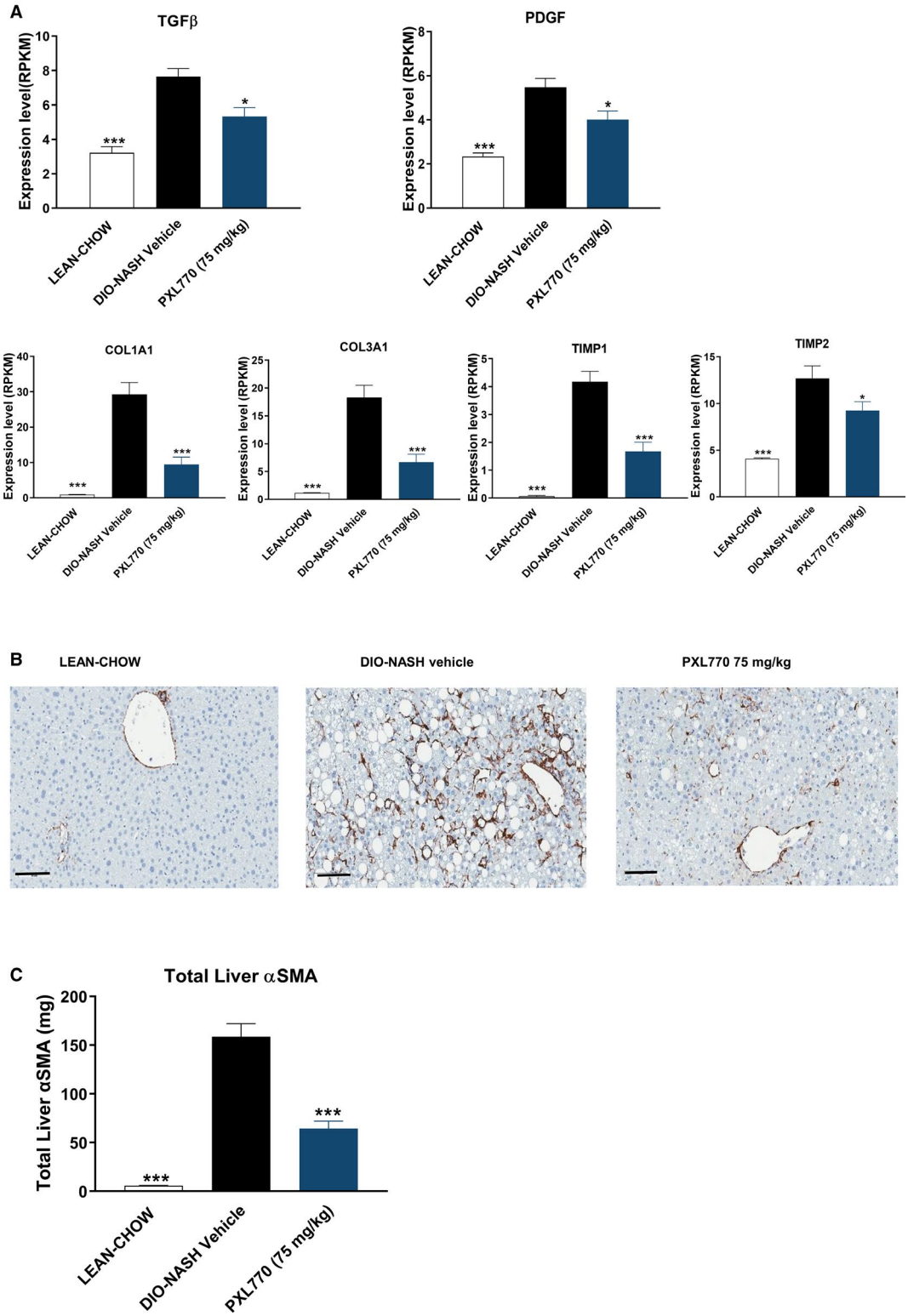

FIG. 6. PXL770 exerts antifibrogenic effects in DIO-NASH mice. (A) Relative messenger RNA expression of indicated genes in liver. (B) α-SMA IHC in liver-tissue sections (magnification, ×20; scale bar, 100 μm). (C) Quantitation of liver α-SMA levels. $^{*}P < 0.05$ and $^{***}P < 0.001$ versus vehicle-treated DIO-NASH (one-way ANOVA); n = 8-12/group.

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with IL1-β increased NF-κB nuclear activity. PXL770 prevented this induction (Fig. 5A). Incubation of adipose explants with PXL770 also inhibited the response to LPS; the induction of secreted IL-1β and IL-6 were significantly attenuated (Fig. 5A). Basal IL-6 secretion was also decreased by PXL770 (Fig. 5A).

PXL770 REDUCES PRO-INFLAMMATORY CYTOKINE PRODUCTION IN HUMAN MACROPHAGES AND PROMOTES TOLEROGENIC DENDRITIC CELLS

To address whether AMPK activation may exert direct anti-inflammatory effects, human macrophages (moMacs) and dendritic cells (moDCs) were used. PXL770 increased AMPK activity in a dose-dependent manner in M1-polarized inflammatory moMacs (Supporting Fig S5A) and simultaneously reduced the production of pro-inflammatory cytokines (TNF-α and IL-6) and chemokine (MCP1) (Fig. 5B). In LPS-primed moDCs, PXL770 also increased AMPK activity in a dose-dependent manner (Supporting Fig S5B) and reduced pro-inflammatory cytokines (TNFα, IL-6, and IL-12p70) (Fig. 5C). Furthermore, PXL770 promoted DC-mediated priming of IL-10-producing CD4 T cells with enhanced regulatory capacity (Fig. 5D). This was associated with decreased expression of the co-stimulatory molecules CD40, CD80 and CD86, and up-regulation of the CD103 tolerogenic marker (Supporting Fig. S5C), whereas neither major histocompatibility complex class II and IL-T3 expression nor DC-mediated Th1, Th2, and Th17 priming were affected (Supporting Fig. S5C,D). Thus, PXL770 has the capacity to directly suppress inflammation while also augmenting anti-inflammatory pathways and cell types.

PXL770 REDUCES LIVER FIBROGENESIS IN DIO-NASH MICE

Vehicle-treated DIO-NASH mice exhibited only mild fibrosis with a score between 1 and 2 (Supporting Fig. S6). Nevertheless, the expression of profibrogenic genes, including those encoding TGF-β and platelet-derived growth factor (PDGF), were increased along with increases in smooth muscle actin (α-SMA), a marker of HSC activation, and an increase in collagen types I and II gene expression (Fig. 6A,B). In parallel, expression levels for tissue inhibitors of matrix metalloproteinases such as tissue inhibitor of metalloproteinase 1 (TIMP1) and TIMP2 were substantially increased (Fig. 6A).

In response to PXL770 treatment, changes in several of the aforementioned parameters were partially reversed. This included reductions of TGF-β1 and PDGF gene expression (Fig. 6A) and decreases in α-SMA protein levels, as assessed by histomorphometry (Fig. 6B). Furthermore, elevated levels of collagen 1A1 and 3A1 gene expression were substantially lowered along with reductions in mean TIMP1 and TIMP2 messenger RNA levels (Fig. 6A).

PXL770 REDUCES ACTIVATION AND PROLIFERATION OF HSCs

Having documented *in vivo* effects on fibrogenesis, we assessed potential direct effects to inhibit HSC activation. In human HSCs, PXL770 suppressed the expression of key activation markers, ACTA2 and COL1A1, along with a strong reduction in procollagen alpha 1 protein secretion with an IC50 ≈ 3 μM (Fig. 7A,B). In addition, PXL770 inhibited TGF-β-induced cell proliferation and the expression of the proliferation marker MIKI67 (Supporting Fig. S7A). NF-κB activation can promote stellate cell activation/proliferation through induction of TNF-α,[36] while SMAD7 inhibits TGF-β-induced stellate cell activation.[37] PXL770 reduced TNF-α and increased SMAD7 gene expression (Fig. 7C), suggesting that this may be important for reducing stellate cell activation/proliferation and would need further investigation. Similar effects were observed in mouse HSCs (Supporting Fig. S7D).

Importantly, the dose-response for markers of fibrogenesis and for measures of target engagement (pAMPK and pACC) were well aligned and were similar with respect to potency in mouse versus human cells (Supporting Fig. S7B,E). As expected from reduced pACC, PXL770 also reduced lipogenesis in HSCs (Fig. 7D, Supporting Fig. S7D). PXL770 also reduced the phosphorylation of p70S6-kinase, a downstream substrate of mammalian target of rapamycin (mTOR), a critical pathway controlling cell growth and proliferation (Supporting Fig. S7B,E).

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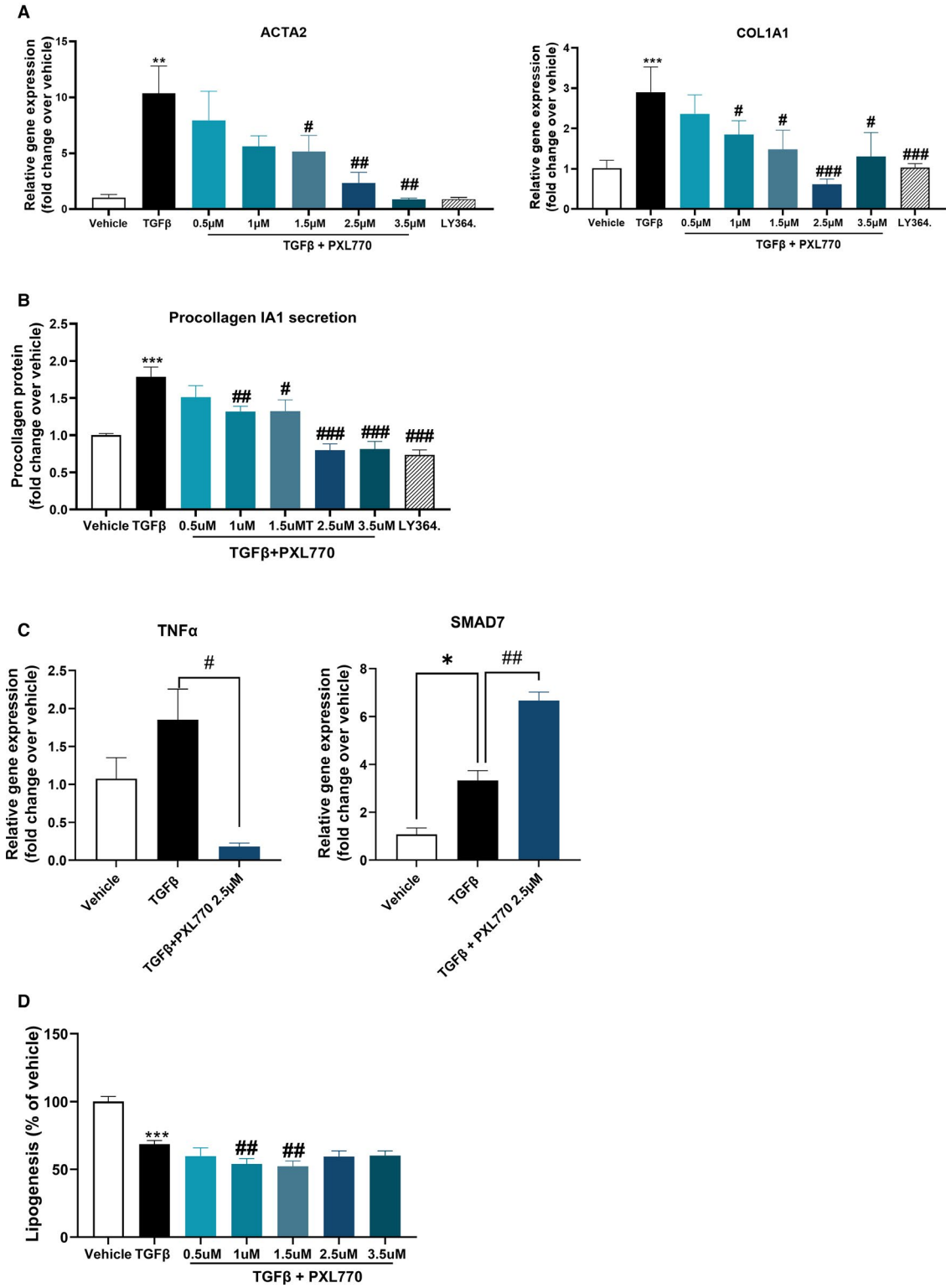

FIG. 7. PXL770 effects on human HSCs. (A) Relative gene expression of ACTA2 and COL1A1 gene. (B) Procollagen 1A1 protein secretion in supernatant. (C) Relative gene expression of TNF-α and SMAD7 gene. (D) Relative lipogenesis. $^{*}P < 0.05$, $^{**}P < 0.01$, and $^{***}P < 0.001$ versus vehicle. $^{\#}P < 0.05$, $^{\#\#}P < 0.01$, and $^{\#\#\#}P < 0.001$ versus TGF-β alone (one-way ANOVA); n = 3 donors, three replicates/donor. (LY364 = LY364947, selective TGF-β receptor 1 inhibitor).

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Discussion

We considered and pursued AMPK as a potential therapeutic target for NASH, given its well-described role as a key metabolic sensor where activation has been implicated in counteracting selected features of NASH pathophysiology.[9,38] Importantly, endogenous AMPK activity is reduced in the context of metabolic dysfunction or inflammation, including in liver and adipose tissue.[39,40]

PXL770 is a small molecule and, to our knowledge, is the only direct AMPK activator that has advanced into human trials in NASH. Our results showed that PXL770 is a direct allosteric AMPK activator, and experiments with site-directed mutants implicate binding to the AMPK β1 CBM domain. These results are consistent with data reported for A769662, a direct AMPK activator that appears to also bind to the ADaM site.[10] AMPK activity was increased by 1.5-fold to 8-fold with PXL770 for most isoforms; this degree of activation is similar to the maximal 2-5-fold effect achieved with AMP—the endogenous activator—in our experiments and in the literature.[41] In contrast, other direct activators have been reported to induce supra-physiologic AMPK activation.[42,43] Potential safety liabilities have been reported with MK-8722,[42] which might relate to markedly greater degrees of activation by this molecule.

Having established PXL770 as a direct AMPK activator, we then tested the hypothesis that PXL770 could favorably affect metabolic parameters that underlie the pathophysiology of NASH. In *ob/ob* mice, a classical obese T2DM model, we observed substantial improvements in HbA1c and elevated plasma TG levels as well as reduced hepatic steatosis. These effects are generally consistent with another report using murine (or non-human primate) models.[42] We also provided definitive evidence of reduced insulin resistance through effects seen during the euglycemic hyperinsulinemic clamp. This represents the first clear evidence of a *bona fide* increase in insulin sensitivity with direct pharmacologic activation of AMPK *in vivo*. This is of particular importance, as insulin resistance is a critical component of the pathogenesis of metabolic diseases including T2DM and NAFLD and a major driver of NASH.[4]

Data from genetic mouse models leading to AMPK deficiency or activation and pharmacological activators clearly indicate that AMPK inhibits hepatic DNL.[12,22,40,41] Here, we confirmed that PXL770 could suppress DNL *in vitro* and *in vivo* in mice during carbohydrate diet refeeding. Our results also suggest that the pro-lipogenic insulin signaling pathway does not override PXL770's effect. The potential for this effect of direct AMPK activation to translate to humans was evident using human hepatocytes, where suppression of DNL occurred with similar potency as in mouse hepatocytes. The significance of this effect is derived from the knowledge that hepatic DNL is increased in patients with NAFLD and accounts for a significant portion of liver lipid accumulation.[31]

Flux of adipose-derived FFAs to liver represents an additional important contributor to steatosis.[4] *In vivo,* we observed that PXL770 decreases plasma FFA and glycerol levels, suggesting an effect of PXL770 to inhibit lipolysis. In addition, changes in HSL phosphorylation, shown with PXL770, support this hypothesis. Although our data are consistent with a reduction in lipolysis, more direct measurements would be required to confirm that this mechanism is involved in reducing steatosis.

Using the well-characterized AMLN diet NASH model,[28,29] we showed that PXL770 improved all hallmarks of NASH pathology, reducing each component of the NASH activity score and several markers of fibrogenesis (including activation of HSCs). Other direct AMPK activators have been shown to ameliorate steatosis in rodents. One such molecule (A-769662) was also shown to improve liver fibrosis in a HFD mouse model,[18] and markers associated with fibrosis were reportedly improved with PF-06409577[26] and Compound 1[27]; however, no effects on inflammation and ballooning were observed. Thus, PXL770 appears to more broadly affect NASH-related parameters in rodents when compared to historical observations with other direct AMPK activators.

Inflammation is a major driver of NASH. A potential role for AMPK was shown in mice lacking the AMPK β1 subunit, where systemic inflammation including increased macrophage infiltration in liver was reported.[15] In addition to reducing hepatic inflammation scores, we documented robust effects of PXL770 to decrease several immune cell types in diseased liver, including monocytes and macrophages (Kupffer cells). Monocytes and macrophages have a major role in NASH, and monocyte-derived cells can develop into macrophages or into DCs, responsible for antigen presentation to adaptative immune cells.[35]

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Monocyte flux to the liver is driven by the chemokine CCL2 (MCP1).[44,45] Thus, reductions in MCP1 may have contributed to the reduction in infiltration of monocytes into liver. To test the hypothesis that PXL770's anti-inflammatory effects were (at least in part) direct (vs. secondary to chronic improvements in insulin resistance and steatosis), we performed several *in vitro* experiments. Using *ob/ob* mouse adipose tissue explants, PXL770 was shown to abrogate activation of NF-κB and concomitantly reduce secretion of several inflammatory cytokines/chemokines: IL-1β, IL-6, and MCP1. Importantly, we also demonstrated clear direct effects to reduce pro-inflammatory cytokines in both human macrophages and DCs. A potential link between AMPK activation and anti-inflammatory effects in macrophages has been previously reported, although *in vitro* effects of direct AMPK activators were not described.[15,46,47] In the current study we also provide the first evidence that direct AMPK activators could exert immunomodulatory effects on human DCs, leading to an "anti-inflammatory" tolerogenic profile characterized by reduced maturation and production of pro-inflammatory cytokines, and an enhanced capacity to skew T-cell responses toward a regulatory phenotype (Tregs). This may be beneficial in the context of NASH, where increased immunogenic "pro-inflammatory" DCs and reduced Tregs have been suggested to contribute to hepatic inflammation.[48,49]

It is well established that inflammation leads to hepatic fibrosis. To ascertain whether antifibrogenic effects observed in liver of DIO-NASH mice could occur through an independent action on HSCs, direct effects of PXL770 were assessed *in vitro*. In both primary mouse and human HSCs, PXL770 strongly reduced activation. Direct AMPK activators have not been previously shown to independently affect HSCs; however, other molecules that promote AMPK activity (e.g., AICAR) have been shown to exert similar effects in mouse HSCs.[50] In addition, PXL770 reduced DNL in this cell type; this effect may contribute to reduced HSC activation, as shown with an ACC inhibitor that was noted to reduce HSC activity.[51]

In summary, we report that activation of AMPK in relevant animal models using PXL770, a direct allosteric activator, targets root causes of NASH including insulin resistance, T2DM, adipose inflammation, and dyslipidemia. Moreover, core features of disease in liver were ameliorated (steatosis, inflammation, and hepatic ballooning). In addition to known effects of direct AMPK activators to modulate DNL, as well as a likely decrease in FFA flux to the liver from the adipose tissue, we demonstrated direct effects to attenuate inflammation and fibrogenesis. These findings, which also included equipotent *in vitro* effects in human versus mouse cells, provide novel insights into the mechanisms underlying potential benefits of AMPK activation in NASH and metabolic syndrome, and support the concept that AMPK activators could have therapeutic utility for the treatment of NASH and related comorbid conditions.

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