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# Adipocyte-Derived PXR Signaling Is Dispensable for Diet-Induced Obesity and Metabolic Disorders in Mice[S]

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## ABSTRACT

**Pregnane X receptor (PXR) is a xenobiotic receptor that can be activated by numerous chemicals including endogenous hormones, dietary steroids, pharmaceutical agents, and environmental chemicals. PXR has been established to function as a xenobiotic sensor to coordinately regulate xenobiotic metabolism by regulating the expression of many enzymes and transporters required for xenobiotic metabolism. Recent studies have implicated a potentially important role for PXR in obesity and metabolic disease beyond xenobiotic metabolism, but how PXR action in different tissues or cell types contributes to obesity and metabolic disorders remains elusive. To investigate the role of adipocyte PXR in obesity, we generated a novel adipocyte-specific PXR deficient mouse model ($PXR^{\Delta Ad}$). Notably, we found that loss of adipocyte PXR did not affect food intake, energy expenditure, and obesity in high-fat diet-fed male mice. $PXR^{\Delta Ad}$ mice also had similar obesity-associated metabolic disorders including insulin resistance and hepatic steatosis as control littermates. PXR deficiency in adipocytes did not affect expression of key adipose genes in $PXR^{\Delta Ad}$ mice. Our findings suggest that adipocyte PXR signaling may be dispensable in diet-induced obesity and metabolic disorders in mice. Further studies are needed to understand the role of PXR signaling in obesity and metabolic disorders in the future.**

## SIGNIFICANCE STATEMENT

**The authors demonstrate that deficiency of adipocyte pregnane X receptor (PXR) does not affect diet-induced obesity or metabolic disorders in mice and infers that adipocyte PXR signaling may not play a key role in diet-induced obesity. More studies are needed to understand the tissue-specific role of PXR in obesity.**

## Introduction

The prevalence of obesity has rapidly increased over the past three decades, and the number of obese and overweight individuals are expected to increase to more than half of the world's population by 2030 (Kelly et al., 2008; Zhou, 2016). Obesity is a major risk factor for developing other chronic diseases including diabetes and cardiovascular disease (Van Gaal et al., 2006; Gregor and Hotamisligil, 2011). Although the contributions of diet and lifestyle to obesity have been well-recognized, the chemical environment to which we are exposed has also changed substantially, and recent studies from us and others have implicated that certain environmental chemicals may act as "obesogens" to increase the risk of obesity (Grün et al., 2006; Grün and Blumberg, 2007; Diamanti-Kandarakis et al., 2009; Casals-Casas and Desvergne, 2011; Heindel and Blumberg, 2019; Egusquiza and Blumberg, 2020).

Many environmental chemicals have been demonstrated to activate the nuclear receptor pregnane X receptor (PXR; also known as steroid and xenobiotic receptor; NR1I2 for standard nomenclature) (Bertilsson et al., 1998; Blumberg et al., 1998; Kliewer et al., 1998, 2002; Zhou et al., 2009b). PXR is a unique nuclear receptor that can be activated by numerous chemicals including dietary steroids, pharmaceutical agents, environmental chemicals, and endogenous hormones (Blumberg et al., 1998; Kliewer et al., 1998; Zhou et al., 2009b; Zhou, 2016). PXR plays a key role in regulating the expression of many enzymes and transporters required for xenobiotic metabolism in the liver and intestine (Blumberg et al., 1998; Kliewer et al., 2002; Zhou et al., 2009b; Zhou, 2016). In the past two decades, the role of PXR as a xenobiotic sensor to regulate xenobiotic metabolism has been well studied by many groups (Zhou et al., 2009b).

Recent studies from our laboratory and others revealed novel functions of PXR in cardiometabolic disease including obesity, diabetes, and cardiovascular disease beyond xenobiotic metabolism (Bhalla et al.,

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F.W. and J.L. contributed equally to this work.

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**ABBREVIATIONS:** BAT, brown adipose tissue; epiWAT, epididymal white adipose tissue; GAPDH, glyceraldehyde-3-phosphate dehydrogenase; HFD, high-fat diet; ND, normal chow diet; PCN, pregnenolone 16α-carbonitrile; PXR, pregnane X receptor; subWAT, subcutaneous white adipose tissue; SV, stromal vascular; WAT, white adipose tissue; WT, wild-type.

2004; Kodama et al., 2004, 2007; de Haan et al., 2009; Zhou et al., 2009a; Cheng et al., 2012; He et al., 2013; Spruiell et al., 2014a, 2014b; Sui et al., 2015; Zhou, 2016; Helsley and Zhou, 2017; Gwag et al., 2019; Meng et al., 2019; Zhang et al., 2023). Several studies have also investigated the function of PXR in obesity and metabolic disorders. For example, He et al. (2013) previously revealed an important role of PXR in obesity by feeding wild-type (WT) and PXR-deficient ($PXR^{-/-}$) mice with a high-fat diet (HFD). Interestingly, they found that deficiency of PXR protected mice from diet-induced obesity and metabolic disorders such as insulin resistance and hepatic steatosis (He et al., 2013). Another study also reported that male $PXR^{-/-}$ mice were resistant to diet-induced obesity (Spruiell et al., 2014b). Paradoxically, male but not female human PXR transgenic mice on PXR-null background (PXR-humanized mice) were also protected from diet-induced obesity (Spruiell et al., 2014a, 2014b). Despite reduced diet-induced obesity, both male $PXR^{-/-}$ and PXR-humanized mice had increased insulin resistance phenotypes (Spruiell et al., 2014b) that were not consistent with the results from the He et al. (2013) study. Although these studies indicate a potential role of PXR in obesity and metabolic disorders, the results were not consistent, suggesting that more studies are needed to establish the function of PXR in diet-induced obesity.

In addition to liver and intestine, PXR is widely expressed in many other tissues and cell types (Owen et al., 2004; Albermann et al., 2005; Siest et al., 2008; Zhou et al., 2009a; Dubrac et al., 2010; Casey et al., 2011; Casey and Blumberg, 2012; Zhou, 2016). As a major energy storage site, adipose tissue also has essential regulatory roles in glucose homeostasis and energy balance during the emergence of obesity (Rosen and MacDougald, 2006). In addition, adipose tissue is also a potential site for toxicant accumulation and may play an important role in the storage and overall toxicokinetics of many xenobiotic chemicals (Jackson et al., 2017). However, the functions of adipocyte PXR remain elusive, partially due to the lack of tissue-specific PXR knockout mice. To investigate the function of adipocyte-derived PXR in obesity and metabolic disorders, we generated a novel adipocyte-specific PXR deficient mouse model. Here, we demonstrate that deficiency of adipocyte PXR does not affect diet-induced obesity or metabolic disorders in male mice and infers that adipocyte PXR may not play an important role in diet-induced obesity in male mice.

## Materials and Methods

**Animals.** To study cell-specific functions of PXR, we previously generated PXR flox mice ($PXR^{F/F}$) on C56BL/6 background carrying loxP-flanked PXR alleles ($PXR^{F/F}$) (Gwag et al., 2019; Sui et al., 2021). To investigate the role of adipocyte PXR signaling, adipocyte-specific PXR knockout ($PXR^{\Delta Ad}$) mice were generated by crossing $PXR^{F/F}$ mice with adiponectin-Cre (Adipoq-Cre) transgenic mice (Eguchi et al., 2011; Park et al., 2016). For the current study, $PXR^{F/F}$ and $PXR^{\Delta Ad}$ had the same PXR flox background but one allele of $PXR^{\Delta Ad}$ mice carries Adipoq-Cre. Four-week-old male $PXR^{F/F}$ and $PXR^{\Delta Ad}$ littermates were fed with either a normal chow diet (ND) or a western-type HFD containing 21.2% fat by weight (42% kcal from fat) (TD88137, Harlan Teklad) for 12 weeks until they were euthanized at 16 weeks of age (Sui et al., 2014; Park et al., 2016; Liu et al., 2023). In addition, male C56BL/6 WT mice were also fed with ND or HFD for 9 weeks. All animal studies were performed in compliance with approved protocols by Institutional Animal Care and Use Committees of University of California, Riverside and University of Kentucky.

**Metabolic Analyses.** For obesity and metabolic phenotypic analyses, bodyweight was measured weekly, and body composition was also analyzed by EchoMRI (Echo Medical System) the day before euthanasia (Helsley et al., 2016; Lu et al., 2019). Intraperitoneal glucose tolerance test and intraperitoneal insulin resistance test were performed as described previously (Helsley et al., 2016; Hernandez et al., 2023; Liu et al., 2023). Food intake, total activity, oxygen consumption ($VO_2$), carbon dioxide production ($VCO_2$), respiratory exchange ratio, and energy expenditure were measured in mice with a LabMaster caging system (TSE Systems) using a separate cohort of male mice (Park et al., 2016). Each mouse was housed individually and monitored for 4–5 consecutive days. $VO_2$, $VCO_2$, and energy expenditure data were normalized by lean body mass and average from 4-day measurements (Park et al., 2016).

**Insulin Stimulation and Glucose Uptake Studies.** For insulin administration studies, insulin (0.35 U/kg body weight) was injected into the inferior vena cava of 16-week-old male $PXR^{F/F}$ and $PXR^{\Delta Ad}$ mice (Park et al., 2016). Mice were euthanized after 5 minutes, and adipose tissues were collected for further protein isolation and Western blotting analysis. For glucose uptake studies, adipose tissue explants were used as previously described (Varlamov et al., 2010; Helsley et al., 2016). HFD-fed male $PXR^{F/F}$ and $PXR^{\Delta Ad}$ mice were used for these studies. Mice were fasted for 7 hours and epididymal white adipose tissue (WAT) was collected and minced into small pieces. The minced tissue explants were then incubated in 1% BSA-Krebs-Ringer bicarbonate buffer for 2 hours in 24-well plates. The explants were then washed before incubating with saline or 17 nM insulin at 37°C for 40 minutes. After the incubation, 1 $\mu$Ci [$^3$H]-2-deoxyglucose (Perkin Elmer) was then added to the wells and incubated at 37°C for 20 minutes. The tissues were washed with cold 1% BSA-Krebs-Ringer bicarbonate buffer and tissue weights were measured. The tissues were incubated in 1 ml 1N NaOH at 65°C for 1 hour. Half of the cell lysate was used for the radioactivity measurement by using a scintillation counter.

**RNA Isolation and Quantitative Real-Time Reverse-Transcription Polymerase Chain Reaction Analyses.** Total RNAs were isolated from mouse tissues or cells using TRIzol Reagent (Thermo Fisher Scientific) as previously described (Sui et al., 2015, 2021; Satta et al., 2022). Adipose stromal vascular (SV) cells and mature adipocytes were isolated from white adipose tissue as we previously described (Sui et al., 2014; Helsley et al., 2016). Quantitative real-time reverse-transcription polymerase chain reaction (QPCR) was performed on a Bio-Rad CFX Real-Time PCR machine by using gene-specific primers and SYBR Green PCR kit (Bio-Rad Laboratories) (Meng et al., 2019; Sui et al., 2021). The sequences of primer sets used in this study are listed in Supplemental Table 1. Glyceraldehyde-3-phosphate dehydrogenase (GAPDH) was used as the reference gene to normalize the mRNA expression.

**Western Blotting.** Proteins were isolated from mouse tissues by homogenization in radioimmunoprecipitation assay buffer with complete mini protease inhibitor cocktail (Roche) as previously described (Meng et al., 2019; Sui et al., 2021). Protein concentrations were measured using the Pierce BCA protein assay kit (Thermo Fisher Scientific). Equal amount of proteins (30 $\mu$g) isolated from different tissues including WAT and liver were used for Western blotting analyses by using antibodies against PXR (Santa Cruz Technology, SC-7739), phosphor-AKT (Cell Signaling Technology, 9271S), AKT (Cell Signaling Technology, 9272) or Actin (Sigma, A2066).

**Tissue Staining and Lipid Analyses.** Liver and WAT were fixed in 4% neutral buffered formalin (Thermo Fisher Scientific, 22-046-361) and embedded in paraffin. Tissue sections (5 $\mu$m) were stained with hematoxylin (Millipore Sigma; 1.05175) and eosin (Millipore Sigma; R03040) as previously described (Sui et al., 2014; Park et al., 2016; Gwag et al., 2019). Oil-Red O staining of hepatic neutral lipids was also performed (Helsley et al., 2016; Gwag et al., 2019). Liver tissues were embedded in optimal cutting temperature and sectioned at 10 $\mu$m. Liver sections were then dried, fixed in 4% paraformaldehyde, incubated for 5 minutes in 60% isopropanol then in 0.3% Oil Red O (Sigma-Aldrich; St. Louis, MO) for 20 minutes. Hepatic total cholesterol and triglyceride contents were also measured (Sui et al., 2014; Gwag et al., 2019). Briefly, 30–50 mg of liver tissues were collected and homogenized in 300–500 $\mu$l Krebs-Ringer buffer (NaCl, 118 mM; KCl, 5 mM; $CaCl_2$, 13.8 mM; $MgSO_4$, 1.2 mM; $K_2HPO_4$, 0.95 mM; and $NaHCO_3$, 25 mM) by sonication for 30 seconds for 10 times. Samples were kept on ice during homogenization. The homogenates were then used for cholesterol and triglyceride assays (Sui et al., 2014; Gwag et al., 2019).

**Statistical Analysis.** All data are presented as the mean ± SD. Individual pairwise comparisons were analyzed by two-sample, two-tailed Student's $t$ test. Two-way ANOVA was used when multiple comparisons were performed (with Bonferroni correction method). Data analyses were performed using GraphPad Prism software and a $P$ value <0.05 was considered significant.

## Results

**Generation of Adipocyte-Specific PXR Knockout Mice.** PXR has been implicated in diet-induced obesity and metabolic disorders, but the functions of PXR in adipose tissues are poorly understood. We found the PXR is expressed in both WAT including subcutaneous (sub) and epididymal (epi) WAT and brown adipose tissue (BAT) of WT mice (Supplemental Fig. 1A). Although the PXR expression levels in adipose tissues were lower than that of PXR-abundant tissues such as liver and small intestine, they were comparable to or even higher than the expression levels of other tissues including kidney and spleen (Supplemental Fig. 1A). In addition, the PXR expression in WAT and BAT was not significantly affected by HFD feeding in WT mice (Supplemental Fig. 1B). To further investigate the role of adipocyte-derived PXR in HFD-induced obesity and metabolic disorders, we generated adipocyte-specific PXR knockout mice ($PXR^{\Delta Ad}$) by crossing mice carrying loxP-flanked PXR alleles ($PXR^{F/F}$) (Gwag et al., 2019; Sui et al., 2021) with Adipoq-Cre transgenic mice (Eguchi et al., 2011; Lee et al., 2013; Park et al., 2016). Previous studies demonstrated that Adipoq-Cre was specifically expressed in the adipose tissue (Eguchi et al., 2011; Lee et al., 2013; Park et al., 2016) and PCR analysis of genomic DNA confirmed that the recombination was specific to the adipose tissues of $PXR^{\Delta Ad}$ mice (Fig. 1A). Western blotting analysis also demonstrated that PXR protein levels were substantially reduced in WAT of $PXR^{\Delta Ad}$ mice as compared with that of control $PXR^{F/F}$ mice (Fig. 1B). Consistently, the mRNA levels of PXR were significantly decreased in both WAT and BAT but not in other major tissues of $PXR^{\Delta Ad}$ mice as compared with $PXR^{F/F}$ mice (Fig. 1C).

Adipoq-Cre has also been shown to be present only in mature adipocytes but not in adipose SV cells (Park et al., 2016). Consistently, we found that the PXR mRNA levels were significantly reduced in mature adipocytes but not SV cells isolated from WAT of $PXR^{\Delta Ad}$ mice (Fig. 1D). Collectively, these results demonstrated the specific and efficient PXR deletion in adipocytes and adipose tissue of $PXR^{\Delta Ad}$ mice.

**Deficiency of PXR in Adipocytes Does Not Affect High-Fat Diet-Induced Obesity in Mice.** To determine the contribution of adipocyte-derived PXR to diet-induced obesity, 4-week-old male $PXR^{F/F}$ and $PXR^{\Delta Ad}$ littermates were fed a ND or HFD for 12 weeks. After 6 weeks of feeding, HFD-fed mice started to have significantly increased body weight as compared with ND-fed mice (Fig. 2A). However, deficiency of adipocyte PXR did not affect diet-induced body weight gain (Fig. 2A). At the end of the study, body composition of these male mice was analyzed by EchoMRI. Although the percentages of fat mass were significantly increased following HFD feeding in both $PXR^{F/F}$ and $PXR^{\Delta Ad}$ mice, adipocyte PXR deficiency had no effects on body composition of $PXR^{\Delta Ad}$ mice under ND or HFD feeding conditions (Fig. 2B). As expected, HFD feeding also led to increased adipocyte size or adipocyte hypertrophy in WAT of obese $PXR^{F/F}$ and $PXR^{\Delta Ad}$ mice, but deficiency of PXR did not cause observable morphology changes in WAT of $PXR^{\Delta Ad}$ mice (Fig. 2C).

Next, we examined different adipose pads of those mice. Consistently, the weights of both subcutaneous white adipose tissue (subWAT) and visceral WAT including epididymal white adipose tissue (epiWAT) and retroperitoneal white adipose tissue were significantly increased in both $PXR^{F/F}$ and $PXR^{\Delta Ad}$ mice after HFD feeding but loss of adipocyte PXR did not affect WAT weight in $PXR^{\Delta Ad}$ mice (Fig. 2D). In

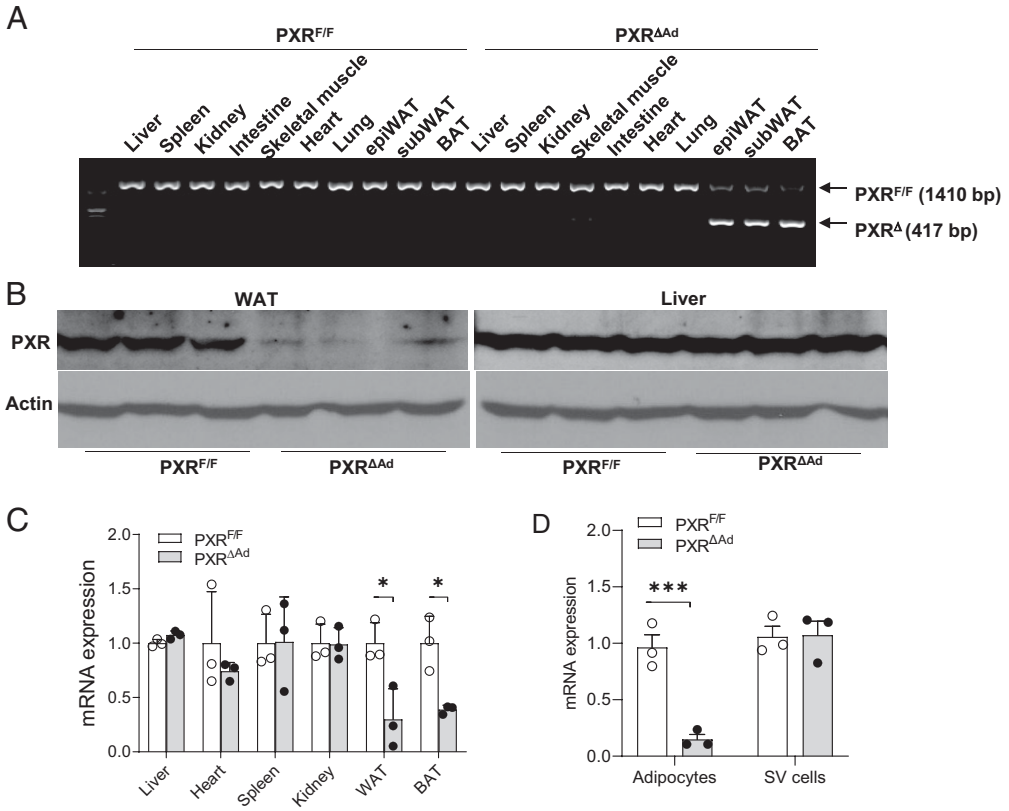


**Fig. 1.** Generation of adipocyte-specific PXR knockout mice. (A) PCR analysis of genomic DNA isolated from major tissues of $PXR^{F/F}$ and $PXR^{\Delta Ad}$ mice showing that Adipoq-Cre–mediated recombination was specific to adipose tissues of $PXR^{\Delta Ad}$ mice. (B) Western blot analysis of PXR protein levels in WAT and liver of $PXR^{F/F}$ and $PXR^{\Delta Ad}$ mice ($n = 3$). (C) mRNA levels of PXR of major tissues, WAT, and BAT from $PXR^{F/F}$ and $PXR^{\Delta Ad}$ mice ($n = 3$, two-sample, two tailed Student's $t$ test, $^*P < 0.05$). (D) mRNA levels of PXR in isolated adipocytes and SV cells from WAT of $PXR^{F/F}$ and $PXR^{\Delta Ad}$ mice ($n = 3$, two-sample, two-tailed Student's $t$ test, $^{***}P < 0.001$).

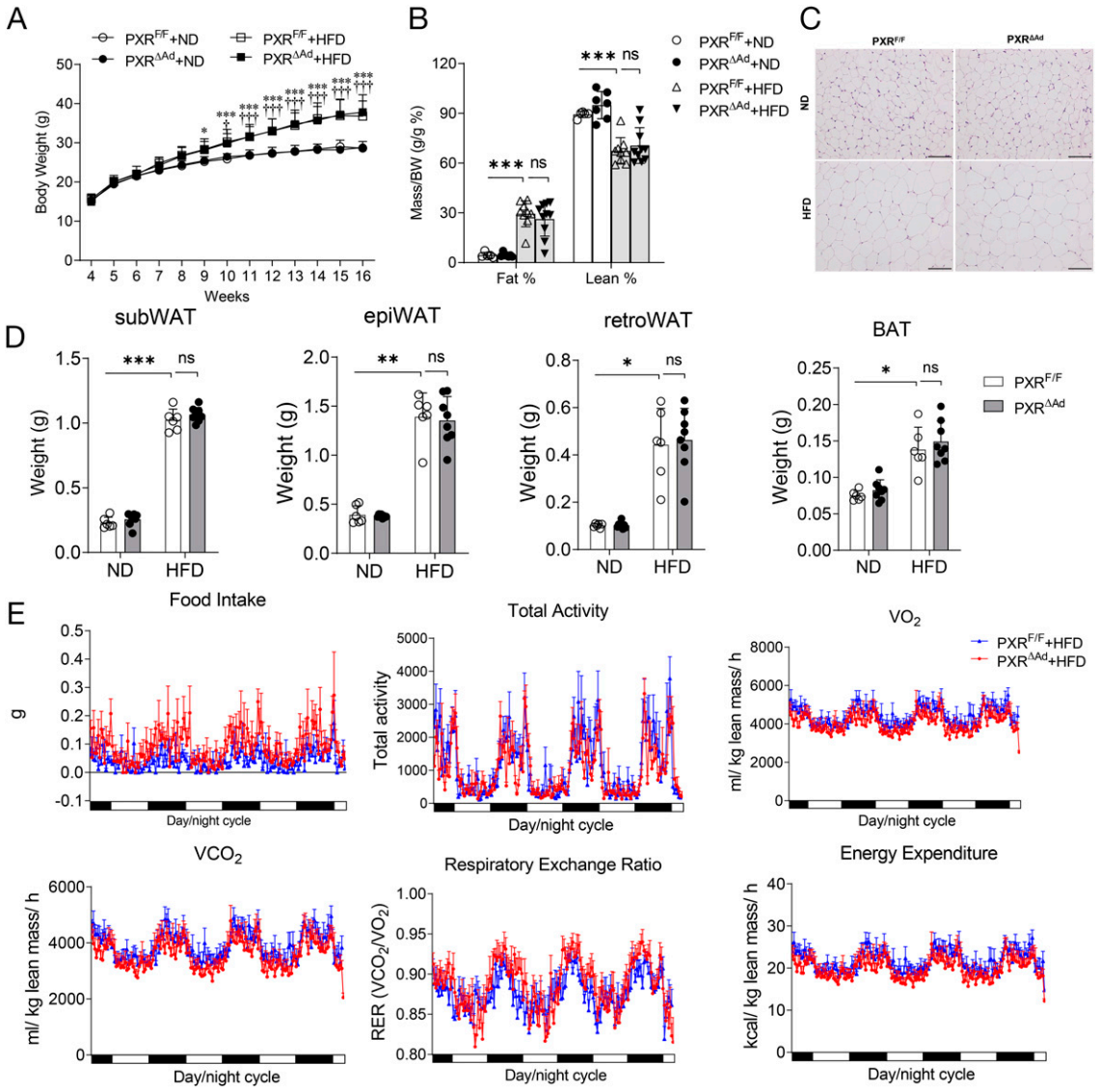


**Fig. 2.** Deficiency of PXR in adipocyte does not affect high-fat diet-induced obesity and metabolic phenotypes in mice. Four-week-old male PXR$^{F/F}$ and PXR$^{\Delta Ad}$ littermates were fed a ND or HFD for 12 weeks. (A–D) Growth curves (A), fat and lean mass (percentage of body weight) (B), representative H&E staining images of WAT (scale bar, 100 $\mu$m) (C), and weight of different adipose pads (epiWAT, subWAT, retroperitoneal WAT, and BAT) (D) of ND or HFD-fed male PXR$^{F/F}$ and PXR$^{\Delta Ad}$ mice ($n$ = 5–10). (E) Metabolic cage analyses of food intake, total activity, oxygen consumption ($VO_2$), carbon dioxide production ($VCO_2$), respiratory exchange ratio, and energy expenditure of HFD-fed PXR$^{F/F}$ and PXR$^{\Delta Ad}$ mice ($n$ = 4-7). Two-way ANOVA followed by Bonferroni's multiple comparison test (*$P$ < 0.05, **$P$ < 0.01, and ***$P$ < 0.001). Statistically significant differences between ND and HFD-fed PXR$^{F/F}$ mice were indicated with * (*$P$ < 0.05, **$P$ < 0.01, and ***$P$ < 0.001). Statistically significant differences between ND and HFD-fed PXR$^{\Delta Ad}$ mice were indicated with † (†$P$ < 0.05 and †††$P$ < 0.001). ns, not significant.

addition, HFD feeding also led to similarly increased BAT weight in both PXR$^{F/F}$ and PXR$^{\Delta Ad}$ mice (Fig. 2D -right panel).

To determine the impact of adipocyte PXR deficiency on energy balance, we also conducted metabolic cage studies using a LabMaster system (Sui et al., 2014; Park et al., 2016). We found that male PXR$^{\Delta Ad}$ mice had similar food intake, total activity, oxygen consumption, carbon dioxide production, and respiratory exchange ratio as the control male PXR$^{F/F}$ mice (Fig. 2E). Therefore, the energy expenditure was not affected by PXR deficiency (Fig. 2E). Taken together, our results suggest that deficiency of PXR in adipocyte does not affect HFD-induced adiposity or obesity in male mice.

**Ablation of Adipocyte PXR Does Not Affect Obesity-Associated Insulin Resistance in PXR$^{\Delta Ad}$ Mice.** Obesity is often associated with increased incidence of metabolic disturbances such as glucose intolerance and insulin resistance. To assess this, we performed glucose tolerance test and insulin tolerance test in those mice. Indeed, we found that obese PXR$^{F/F}$ and PXR$^{\Delta Ad}$ mice had worse glucose tolerance (Fig. 3A) and exhibited reduced hypoglycemic response to administered insulin (Fig. 3B). However, deficiency of PXR did not affect glucose tolerance test and insulin tolerance test results in ND-fed or HFD-fed mice.

To further investigate the impact of adipocyte PXR deficiency on adipose insulin signaling, HFD-fed male mice were injected with insulin before euthanasia and phosphorylation of Akt in WAT was analyzed (Helsley et al., 2016). Insulin treatment led to enhanced phosphorylation of Akt in WAT; however, deficiency of PXR did not affect insulin-stimulated phosphorylation of Akt (Fig. 3C). Next, we performed ex vivo adipose glucose uptake assays. As expected, insulin treatment also increased glucose uptake by adipose tissue of both PXR$^{F/F}$ and PXR$^{\Delta Ad}$ mice (Fig. 3D). However, deletion of PXR did not affect the adipose glucose uptake under basal or insulin-stimulated conditions. Taken

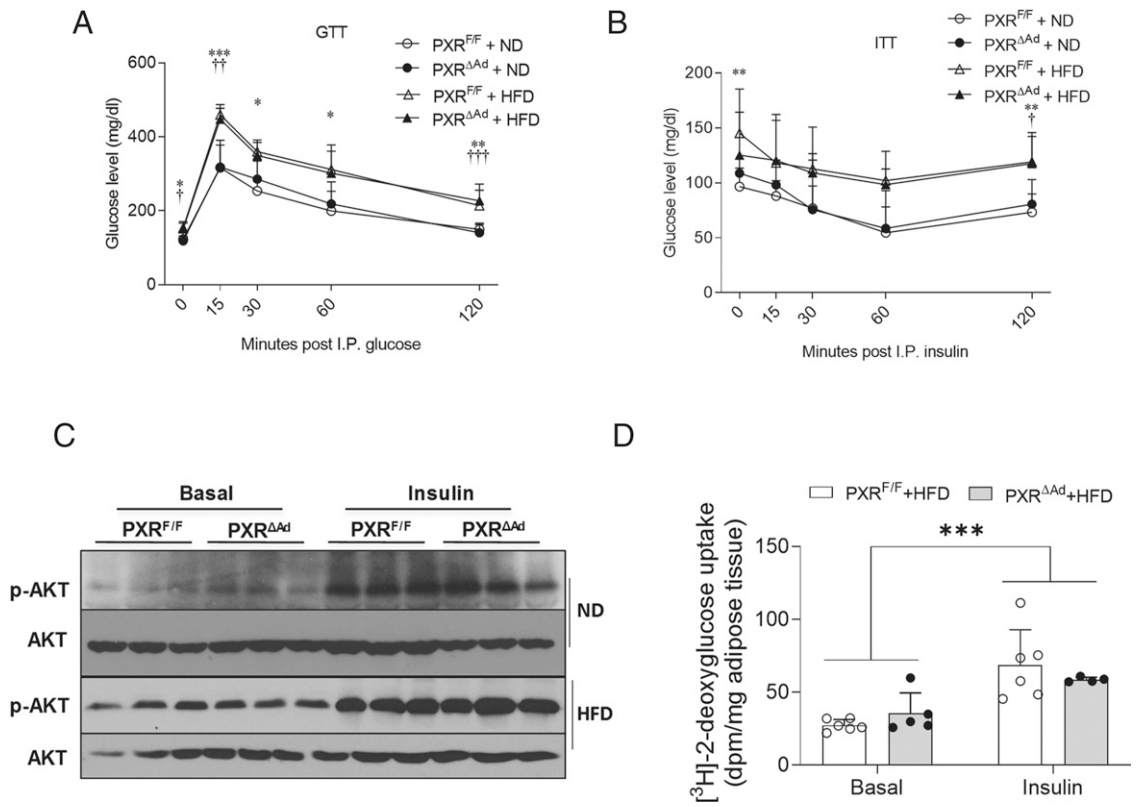


**Fig. 3.** Ablation of PXR does not affect obesity-associated insulin resistance in PXR$^{\Delta Ad}$ mice. Four-week-old male PXR$^{F/F}$ and PXR$^{\Delta Ad}$ littermates were fed a ND or HFD for 12 weeks. (A and B) Intraperitoneal glucose tolerance test (A) and intraperitoneal insulin resistance test (B) of PXR$^{F/F}$ and PXR$^{\Delta Ad}$ mice ($n$ = 5–10). (C) Western blotting analysis of phosphorylated-AKT and total AKT in adipose tissue after stimulated with saline or 0.35 units/kg body weight insulin for 5 minutes ($n$ = 3). (D) Glucose uptake was measured in primary adipose tissues from HFD-fed PXR$^{F/F}$ and PXR$^{\Delta Ad}$ mice ($n$ = 4–6). Two-way ANOVA followed by Bonferroni's multiple comparison test (***$P$ < 0.001). Statistically significant differences between ND and HFD-fed PXR$^{F/F}$ mice were indicated with * (*$P$ < 0.05, **$P$ < 0.01, and ***$P$ < 0.001). Statistically significant differences between ND and HFD-fed PXR$^{\Delta Ad}$ mice were indicated with † (†$P$ < 0.05, ††$P$ < 0.01, and †††$P$ < 0.001).

together, these studies indicated that adipocyte PXR does not play a significant role in obesity-associated insulin resistance in mice.

**Ablation of Adipocyte PXR Does Not Affect Expression of Key Adipose Tissue Genes.** We next investigated how deficiency of adipocyte PXR affects key adipose gene expression in WAT (Fig. 4A) and BAT (Fig. 4B) of male PXR$^{F/F}$ and PXR$^{\Delta Ad}$ mice. As expected, we found that HFD feeding led to increased expression of several key genes mediating adipose tissue differentiation (e.g., peroxisome proliferator-activated receptor $\gamma$, adipocyte protein 2), $\beta$-oxidation (e.g., carnitine palmitoyltransferase 1b), and lipogenesis (e.g., peroxisome proliferator-activated receptor $\alpha$) in WAT and BAT in both PXR$^{F/F}$ and PXR$^{\Delta Ad}$ mice. However, deletion of adipocyte PXR had no significant effects on the expression of these genes in PXR$^{\Delta Ad}$ mice (Fig. 4A). In addition, obese mice also had reduced expression of several WAT genes regulating glucose metabolism, including glucose transporter 4 and insulin receptor substrate 1, and key BAT genes, including uncoupling protein 1 and PR domain zinc finger protein 16 of PXR$^{F/F}$ and PXR$^{\Delta Ad}$ mice. However, PXR deficiency did not affect HFD-mediated reduction of those genes in PXR$^{\Delta Ad}$ mice (Fig. 4B).

**Deficiency of Adipocyte PXR Does Not Alleviate High-Fat Diet-Induced Hepatic Steatosis in Mice.** In addition to insulin resistance, obesity is frequently accompanied by other disorders such as hepatic steatosis. As expected, high-fat feeding led to increased lipid accumulation and hepatic steatosis in the liver of PXR$^{F/F}$ mice as indicated by H&E and Oil-red O staining, but deficiency of adipocyte PXR did not affect HFD-induced hepatic steatosis in PXR$^{\Delta Ad}$ mice (Fig. 5, A and B). Hepatic cholesterol and triglyceride contents were also significantly increased in HFD-fed male PXR$^{F/F}$ and PXR$^{\Delta Ad}$ mice as compared with ND-fed mice (Fig. 5C). Consistently, there is no significant differences for hepatic cholesterol and triglyceride levels between male PXR$^{F/F}$ and PXR$^{\Delta Ad}$ mice under either ND-fed or HFD-fed conditions. Hepatic gene expression analysis then revealed that deficiency of PXR did not affect the expression of several key hepatic genes regulating lipogenesis (e.g., stearoyl-coenzyme A desaturase 1) and gluconeogenesis (e.g., phosphoenolpyruvate carboxykinase and glucose 6-phosphatase) in male PXR$^{\Delta Ad}$ mice (Fig. 5D). These results indicate that ablation of PXR in adipocytes has no significant effects on HFD-induced hepatic steatosis and altered key hepatic gene expression.

## Discussion

As a key xenobiotic receptor, the functions of PXR in regulating xenobiotic metabolism have been extensively investigated by many groups, and the role of PXR as a xenobiotic sensor has been established (Blumberg and Evans, 1998; Kliewer et al., 2002; Zhou et al., 2009b). New evidence has suggested novel functions of PXR beyond xenobiotic metabolism, and several studies have also indicated that PXR may play an important role in obesity and metabolic disorders (Zhou, 2016; Zhang et al., 2023). However, the cell-type–specific functions of PXR in obesity have not been investigated. Adipose tissue is the main body energy storage site and adipocyte dysfunction contributes significantly to obesity-associated metabolic disorders. Adipocytes have also been considered as a prominent storage site of lipophilic chemicals, and adipose tissue has been implicated to play an important role in the storage

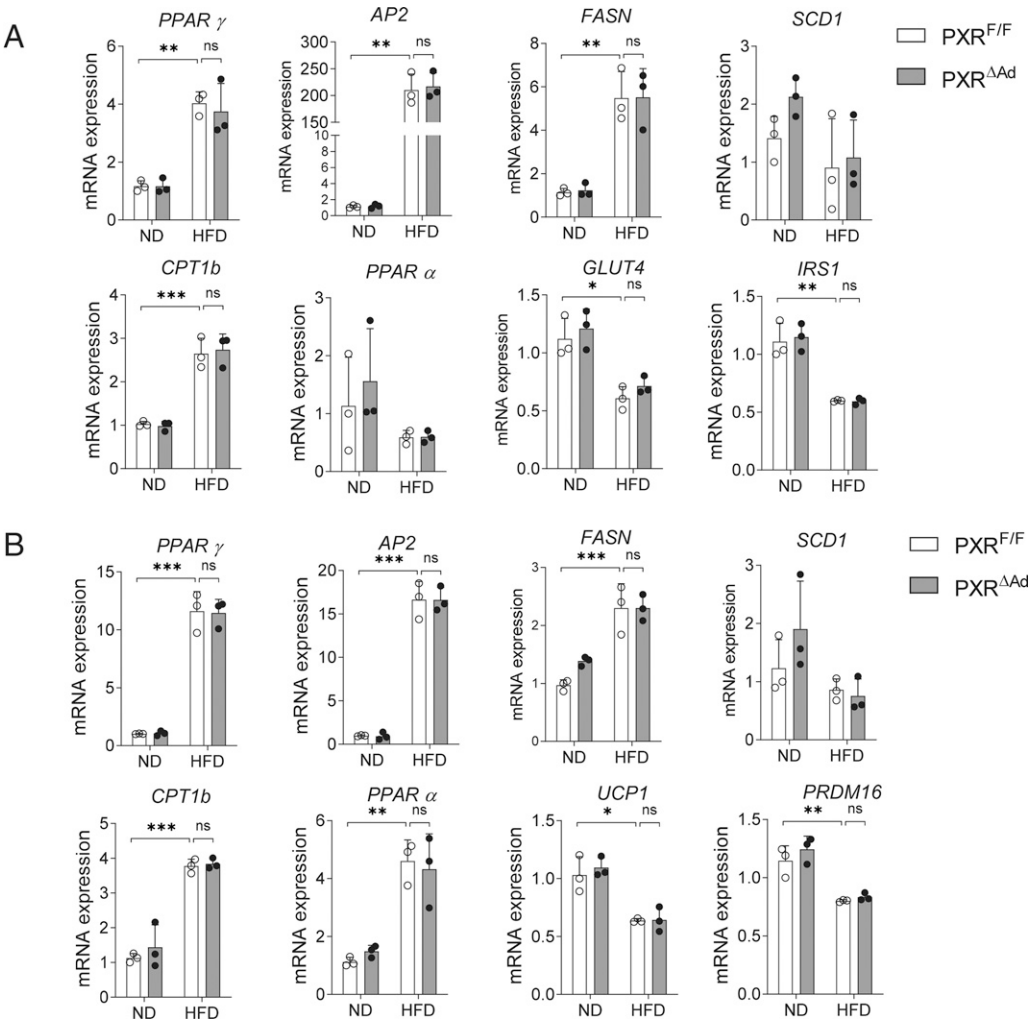


**Fig. 4.** Ablation of PXR does not affect key adipose tissue gene expression. Four-week-old male $PXR^{F/F}$ and $PXR^{\Delta Ad}$ littermates were fed a HFD for 12 weeks. QPCR analyses of indicated genes in WAT (A) and BAT (B) ($n = 3$). GAPDH was used as the reference gene to normalize the mRNA expression. Two-way ANOVA followed by Bonferroni's multiple comparison test (*$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$). ns, not significant. PPAR$\gamma$, peroxisome proliferator-activated receptor $\gamma$; AP2, adipocyte protein 2; FASN, fatty acid synthase; SCD1, stearoyl-coenzyme A desaturase 1; CPT1b, carnitine palmitoyltransferase 1b; PPAR$\alpha$, peroxisome proliferator-activated receptor $\alpha$; GLUT4, glucose transporter 4; IRS1, insulin receptor substrate 1; UCP1, uncoupling protein 1; PRDM16, PR domain zinc finger protein 16.

and toxicokinetics of hydrophobic xenobiotics (Jackson et al., 2017). In the current study, we generated novel adipocyte-specific PXR-deficient mice to explore the functions of adipocyte PXR in diet-induced obesity and metabolic disorders. Interestingly, we found that loss of adipocyte PXR did not significantly affect food intake, energy expenditure, or diet-induced obesity in male mice. In addition, deficiency of adipocyte PXR did not alleviate obesity-associated metabolic disorders including insulin resistance and hepatic steatosis in mice. Our results suggested that adipocyte PXR signaling plays only a minimal role in diet-induced obesity and metabolic disorders in mice (Fig. 6).

Previous studies using whole-body PXR knockout or transgenic mice suggested that PXR plays a complex role in diet-induced obesity and metabolic disorders. For example, He et al. (2013) also found that deficiency of PXR did not affect food intake in $PXR^{-/-}$ mice. Consistently, we also found that $PXR^{\Delta Ad}$ mice had similar food intake as control littermates. However, the whole-body PXR-deficient mice were resistant to diet-induced obesity, likely due to the increased oxygen consumption and mitochondrial $\beta$-oxidation in those mice (He et al., 2013). In addition, $PXR^{-/-}$ mice were also protected from obesity-associated insulin resistance and hepatic steatosis (He et al., 2013). Those authors also crossed $PXR^{-/-}$ mice with leptin-deficient ob/ob mice to investigate the role of PXR under genetic obesity condition. They found that PXR-deficient, ob/ob mice had increased oxygen consumption and energy expenditure (He et al., 2013). Consistently, deficiency of PXR led to decreased obesity and diabetic condition in ob/ob mice (He et al., 2013). In our study, deficiency of adipocyte PXR did not affect oxygen consumption, carbon dioxide production, or energy expenditure. It is plausible that PXR signaling in other cell types other than adipocytes play an important role in regulating energy expenditure.

In contrast to the findings of He et al. (2013), another study showed that activation of PXR by treating mice with the PXR ligand pregnenolone 16$\alpha$-carbonitrile (PCN) prevented diet-induced obesity, insulin resistance, and hepatic steatosis (Ma and Liu, 2012). However, these studies were conducted in a different mouse strain, AKR/J mice instead of C57BL/6J mice. In addition, Ma and Liu (2012) also found that PCN-mediated PXR activation can affect adipocyte differentiation and lipid metabolism-related gene expression in adipose tissue of AKR/J mice. We found that deficiency of adipocyte PXR did not affect the expression of key adipose genes in either WAT or BAT. It is well-known that different strains have different susceptibilities to various diseases

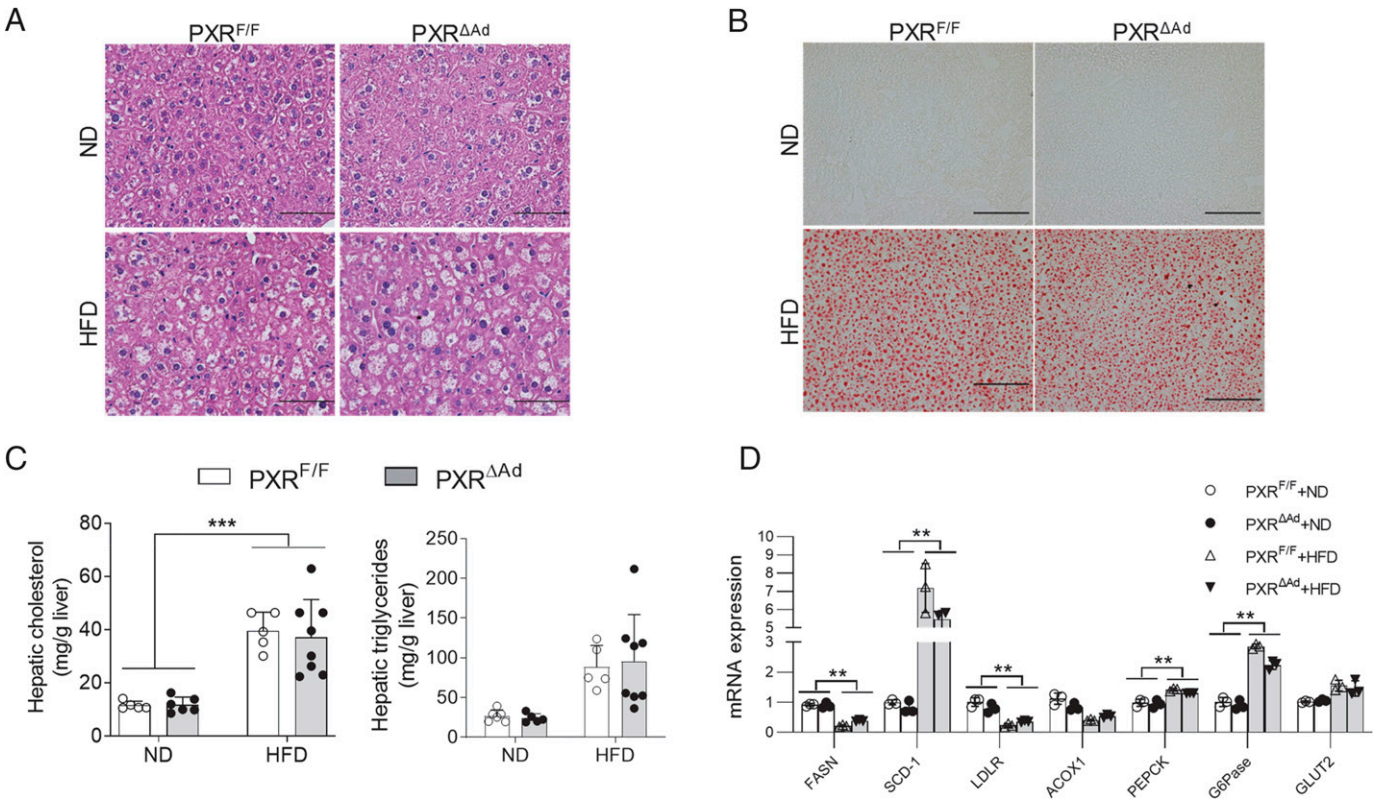


**Fig. 5.** Deficiency of adipocyte PXR does not alleviate high-fat diet-induced hepatic steatosis in mice. Four-week-old male $PXR^{F/F}$ and $PXR^{\Delta Ad}$ littermates were fed a ND or HFD for 12 weeks. (A and B) Representative H&E (scale bar, 50 $\mu$m) (A) and Oil red O (scale bar, 100 $\mu$m) (B) stained liver sections of ND and HFD-fed $PXR^{F/F}$ and $PXR^{\Delta Ad}$ mice. (C) Hepatic cholesterol and triglyceride levels from $PXR^{F/F}$ and $PXR^{\Delta Ad}$ mice fed a ND or HFD ($n$ = 5–8). (D) QPCR analysis of indicated hepatic genes of $PXR^{F/F}$ and $PXR^{\Delta Ad}$ mice ($n$ = 3). GAPDH was used as the reference gene to normalize the mRNA expression. Two-way ANOVA followed by Bonferroni's multiple comparison test (**$P$ < 0.01 and ***$P$ < 0.001). FASN, fatty acid synthase; SCD1, stearoyl-coenzyme A desaturase 1; LDLR, low density lipoprotein receptor; ACOX1, acyl-CoA oxidase 1; PEPCK, phosphoenolpyruvate carboxykinase; G6Pase, glucose 6-phosphatase; GLUT2, glucose transporter 2.

including obesity and diabetes. Therefore, it is possible that PXR signaling may interact with different pathways or regulate different genes in AKR/J mice than in C57BL/6J mice. Ma and Liu (2012) also used relatively high concentrations of PCN (50 mg/kg) and did not conduct a similar study in PXR-deficient mice. Therefore, the observed beneficial effects of PCN treatment may not be completely attributable to PXR signaling but may involve other signaling pathways such as glucocorticoid receptor signaling.

In addition to genetic backgrounds, Spruiell et al. (2014b) showed that PXR signaling may have sex-specific effects on obesity and diabetes. They found that deficiency of PXR protected male mice from diet-induced obesity, which was consistent with the findings of He et al. (2013). Surprisingly, male PXR-humanized mice expressing human PXR instead of mouse PXR were also resistant to obesity. However, the same group found that female PXR-humanized mice were not resistant but rather susceptible to diet-induced obesity (Spruiell et al., 2014a). Despite different obesity phenotypes, both male and female PXR-humanized mice had exacerbated diabetic phenotypes including elevated plasma glucose or insulin levels and impaired glucose tolerance (Spruiell et al., 2014a, 2014b). In the current study, all $PXR^{F/F}$ and $PXR^{\Delta Ad}$ littermates used for obesity and metabolic function studies were males. One of reasons to select male mice for this study is that female C56BL/6 mice are relatively resistant to diet-induced obesity as compared with male mice (Hong et al., 2009). Estrogen has been shown to play an important role in the regulation of energy homeostasis and may have protective effects from obesity complications (Clegg, 2012; Lizcano and Guzmán, 2014), which makes studying obesity phenotype in female mice more complicated. Indeed, ovariectomized female C56BL/6 mice can gain more weight and adipose tissue as compared with sham female mice (Rogers et al., 2009). However, this is also an important limitation of our study because sex differences have been well recognized in murine and human obesity and metabolic disease studies. It would be interesting to study whether adipocyte PXR may have different effects on obesity and metabolic functions in female mice in the future.

Liver plays a key role in regulating whole body glucose homeostasis (Nordlie et al., 1999; Lin and Accili, 2011). Spruiell et al. (2014a, 2014b) previously suggested that the diabetic phenotypes in male and female PXR-humanized mice were partially due to dysregulated glucose metabolism in the liver. He et al. (2013) also demonstrated that transgenic activation of PXR in the liver exacerbated the diabetic phenotypes of ob/ob mice. PXR has been shown to regulate hepatic glucose and energy homeostasis through multiple mechanisms, including crosstalk with forkhead box protein O1 (FoxO1) and FoxA2 pathways (Kodama et al., 2004; Nakamura et al., 2007) and regulating genes involved in glucose uptake and gluconeogenesis (Bhalla et al., 2004; Kodama et al., 2007; Hassani-Nezhad-Gashti et al., 2018). We found that PXR deficiency in adipocytes did not cause observable liver phenotypes, and the expression of several key hepatic genes regulating lipogenesis and gluconeogenesis was also unaffected in $PXR^{\Delta Ad}$ mice. Therefore, it is possible that hepatic PXR, but not adipocyte PXR, plays an important role in diet-induced metabolic disorders. In addition to liver, PXR is also expressed in many immune cells including macrophages (Owen et al., 2004; Albermann et al., 2005; Zhou et al., 2009a; Sui et al., 2020). Macrophages also play important roles in obesity-associated insulin

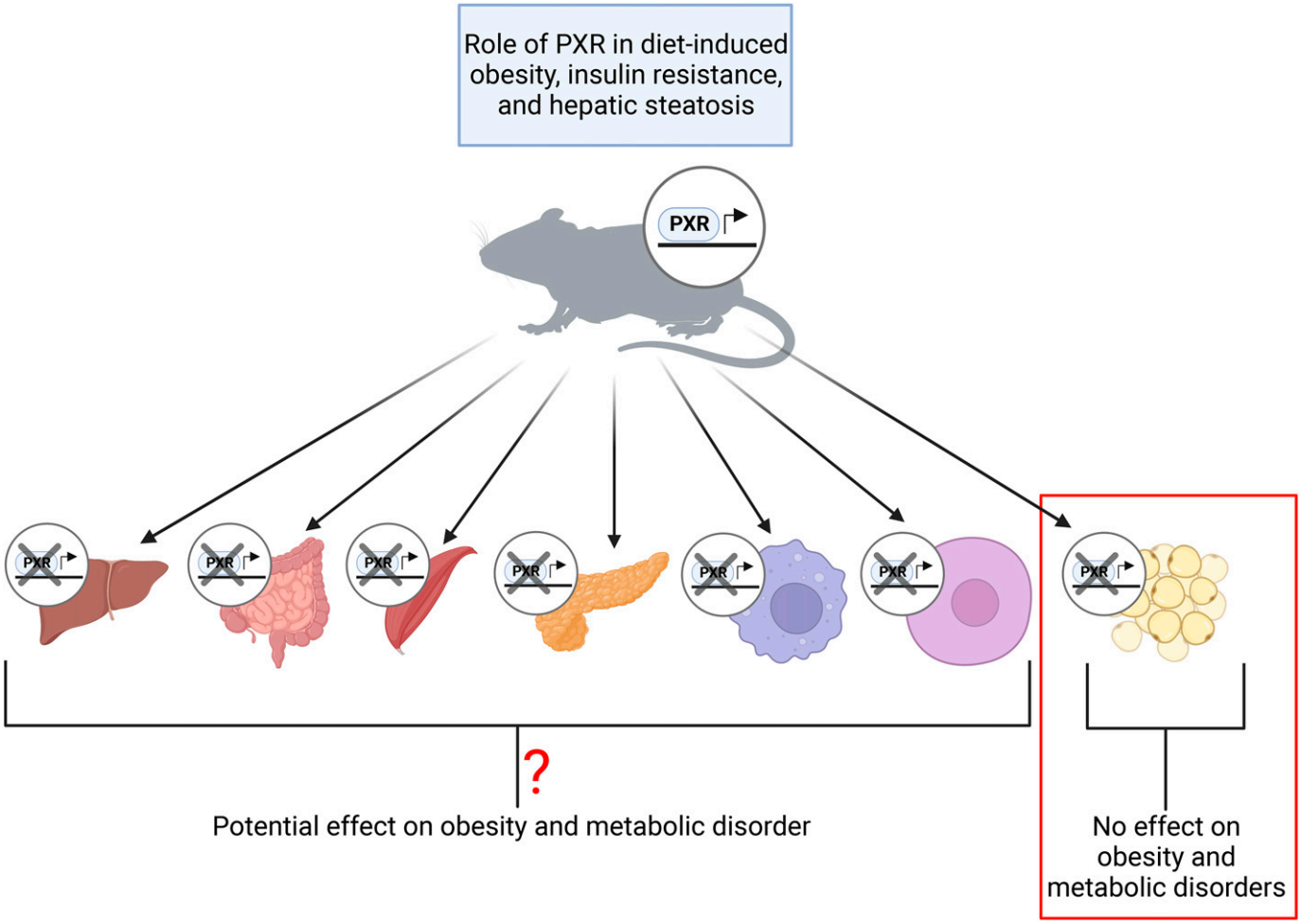


**Fig. 6.** Schematic of the potential role of PXR signaling in diet-induced obesity and metabolic disorders. PXR signaling has been implicated in diet-induced obesity, insulin resistance, and hepatic steatosis. Results from the current study demonstrate that deficiency of adipocyte PXR does not affect diet-induced obesity or metabolic disorders in male mice, indicating that adipocyte PXR may not play an important role in obesity. However, PXR is expressed in many other tissues and cell types. Future studies are required to investigate how PXR signaling in those tissues or cell types including liver, intestine, skeletal muscle, pancreas, macrophages, and adipose progenitors regulates diet-induced obesity and metabolic disorders.

resistance and diabetes (Olefsky and Glass, 2010; Park et al., 2016; Ying et al., 2017). We previously generated myeloid-specific PXR-deficient mice and revealed the important function of myeloid PXR signaling in regulating atherosclerosis development (Sui et al., 2020). Under low-fat diet feeding condition, deficiency of myeloid PXR did not affect body weight, body composition, or metabolic phenotypes in lean mice (Sui et al., 2020). However, it is not clear whether PXR signaling functions in macrophages to regulate metabolic phenotypes in obese mice. Future studies are required to investigate how PXR functions differently in different cell types to modulate obesity and metabolic functions (Fig. 6).

It is also important to note that our study investigated the adipocyte PXR function under ND and HFD feeding conditions without exposing the mice to PXR ligands. Many xenobiotic chemicals, including some obesogens, have been shown to target nuclear receptor signaling to affect adipose tissue expansion and function, leading to increased obesity and metabolic disorders (Grün and Blumberg, 2006; Heindel and Blumberg, 2019; Egusquiza and Blumberg, 2020). Because many of those chemicals have been identified as PXR ligands (Kretschmer and Baldwin, 2005; Zhou, 2016; Helsley and Zhou, 2017), it would be interesting to study whether adipocyte PXR plays a role in diet-induced obesity and metabolic disorders when the mice are under xenobiotic stress or exposed to PXR-activating xenobiotics in the future.

In summary, we generated a novel $PXR^{\Delta Ad}$ mouse model to investigate the role of adipocyte PXR in diet-induced obesity and metabolic disorders. We found that deficiency of adipocyte PXR did not affect body weight gain or body composition in HFD-fed male mice. Obese $PXR^{\Delta Ad}$ mice also had similar metabolic disorders including insulin resistance and hepatic steatosis as control littermates. Further, deficiency of PXR in adipocytes did not affect key adipose gene expression in $PXR^{\Delta Ad}$. These results suggest that adipocyte PXR signaling may not have indispensable function in diet-induced obesity and metabolic disorders. Although the negative results obtained from this study may make the study of PXR and obesity more challenging, we believe that these null results are still important and informative for future research directions on this topic. Further investigations are needed to better understand the role of PXR signaling in obesity and metabolic disorders.

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**Data Availability**

The data supporting the findings of this study are contained within the paper.

## Authorship Contributions

*Participated in research design:* Wang, Blumberg, Zhou.
*Conducted experiments:* Wang, Liu, Hernandez, Park, Lai.
*Contributed new reagents or analytic tools:* Wang, Blumberg, Zhou.
*Performed data analysis:* Wang, Liu, Hernandez, Park, Lai, Wang, Zhou.
*Wrote or contributed to the writing of the manuscript:* Wang, Liu, Hernandez, Blumberg, Zhou.

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