Metformin increases hepatic leptin receptor and decreases steatosis in mice

Xuemei Tang1,2,*, Jingwen Li1,2,*, Wei Xiang1, Ye Cui2, Bin Xie3, Xiaodong Wang4, Zihui Xu2 and Lixia Gan1

1Department of Biochemistry and Molecular Biology, Third Military Medical University, Chongqing, China
2Department of Integrated Medicine, Xinqiao Hospital, Third Military Medical University, Chongqing, China
3Department of Hepatobiliary Surgery, Daping Hospital & Institute of Surgery Research, Third Military Medical University, Chongqing, China
4Institute of Pathology, Southwest Hospital, Third Military Medical University, Chongqing, China
*(X Tang and J Li contributed equally to this work)

Abstract
In addition to the ascertained efficacy as antidiabetic drug, metformin is increasingly being used as weight-loss agent in obesity, and as insulin sensitizer in nonalcoholic fatty liver disease (NAFLD). However, the mechanisms underlying these effects are still incompletely understood. Emerging evidence suggest metformin as leptin sensitizer to mediate the weight-loss effect in the brain. In this study, we investigated effects of metformin on expression of leptin receptors in liver and kidney in mice. C57BL/6 mice were fed with chow diet (CD) or high-fat diet (HF) for 5 months. Afterward, mice were treated with metformin (50 mg/kg or 200 mg/kg) for 15 days. Metabolic parameters and hepatic gene expression were analyzed at the end of the treatment. We also tested the effects of metformin on plasma-soluble leptin receptor (sOB-R) levels in newly diagnosed type 2 diabetes mellitus (T2DM) patients, and assessed its effect on hepatosteatosis in mice. Results showed that metformin upregulates the expression of leptin receptors (OB-Ra, -Rb, -Rc, and -Rd) in liver but not kidney. The stimulation effect is dose-dependent in both chow and HF mice. Upregulation of OB-Rb, long signaling isoform, needs a relatively higher dose of metformin. This effect was paralleled by increased sOB-R levels in mice and T2DM patients, and decreased hepatic triglyceride (TG) content and lipogenic gene expression, including sterol regulatory element-binding protein 1c (SREBP-1c), fatty acid synthase (FAS) and acetyl-CoA carboxylase-1 (ACC-1). Taken together, these data identify hepatic leptin receptor as target gene being upregulated by metformin which may enhance leptin sensitivity in liver to alleviate steatosis.

Key Words
- metformin
- leptin receptor
- soluble leptin receptor
- liver steatosis

Introduction
Metformin is the first-line antihyperglycemia agent for T2DM patients. The mechanisms by which metformin improves glycemic control is mainly by reducing hepatic glucose production, and to a lesser extent, via enhancing peripheral insulin sensitivity, blocking gastrointestinal glucose absorption, modulating gut microbiota and promoting incretin axis (Ikeda et al. 2000, Green et al. 2006, Maida et al. 2011, Miller et al. 2013, Foretz et al. 2014, ...
Madiraju et al. 2014, Shin et al. 2014). In addition to its antidiabetic effects, metformin demonstrates multiple beneficial ‘side effects’ such as antiobesity, antihepatosteatotic and anti-inflammatory effects, and is currently in clinical trials to treat obesity (Malin & Kashyap 2014), NAFLD (Zheng et al. 2015), polycystic ovary syndrome (PCOS) (Misso & Teede 2015) and certain types of cancer (Leone et al. 2014, Morales & Morris 2015). Emerging evidence suggests that enhanced leptin sensitivity may contribute to the weight-loss effect of this drug (Aubert et al. 2011, Malin & Kashyap 2014). However, literature regarding metformin as leptin sensitizer is so far scarce.

Leptin is an adipocyte-derived hormone that exerts powerful effects both centrally and peripherally. In the brain, leptin inhibits food intake, promotes energy expenditure and regulates autonomic nerve control, thus playing a key role in body weight regulation (Zhang et al. 1994, Flak & Myers 2016). In peripheral tissues, leptin directly acts on liver, muscle or pancreas to promote fat oxidation (Muioio & Lynis Dohm 2002) or inhibiting insulin secretion (Marroqui et al. 2012). Mutations in the functional leptin (ob/ob) or leptin receptors gene (db/db) in mice and humans display abnormalities ranging from hyperphagia, diabetes, hypercortisolemia, infertility, cold intolerance to fatty liver and skeleton aberrations (Coleman 1982, Montague et al. 1997, Clément et al. 1998, Farooqi et al. 2007). Leptin replacement therapy reverses these abnormalities in leptin-deficient animals and patients. However, instead of lacking this hormone, most obese individuals (humans and animals) have elevated serum levels of leptin but with blunted response to the endogenous or exogenous leptin, a state which is defined as leptin resistance. Central leptin resistance plays a key role in pathogenesis of obesity (Caro et al. 1996, de Luca et al. 2005, Myers et al. 2010), while hepatic leptin resistance is a key determinant of lipid accumulation in liver (Fishman et al. 2007). Therefore, rescuing leptin sensitivity would provide opportunity to reverse obesity-associated diseases.

Leptin acts primarily by binding to a signaling leptin receptor, known as long isoform OB-Rb (Flak & Myers 2016), whereas short receptor isoforms, OB-Ra, -Rc and -Rd, modulate leptin bioavailability and function via two mechanisms: control of leptin transport across the blood–brain barrier (BBB) (Kastin et al. 1999) and proteolytic cleavage production as sOBR, the major leptin-binding protein in circulation (Maamra et al. 2001, Ge et al. 2002). Much evidence indicate sOBR serve as a novel biomarker for leptin sensitivity. Decreased sOBR levels have been negatively correlated with increased obesity, serum leptin level, fasting plasma glucose (FPG), fasting insulin (FINs) and homeostasis model assessment of insulin resistance (HOMA-IR), biomarkers for hyperglycemia, leptin and insulin resistance (Ogawa et al. 2004, Hamnvik et al. 2011). However, increased sOBR levels have been positively correlated with high-density lipoprotein (HDL)-cholesterol and serum adiponectin levels (Ogawa et al. 2004, Hamnvik et al. 2011, Yu et al. 2011). In a recent large prospective study, increased plasma sOBR levels are associated with lowered risk of T2DM (Sun et al. 2010). In support, mice overexpressing sOBR demonstrated reduced food intake, increased basal metabolic rate and increased lipid oxidation, metabolic phenotypes of higher leptin sensitivity (Lou et al. 2010). In agreement, liver-specific insulin receptor knockout (LIRKO) mice displays markedly increased sOBR levels in circulation and enhanced leptin sensitivity (Cohen et al. 2007). Moreover, obese subjects after weight loss surgery (Laimer et al. 2002, Siejka et al. 2013), diet therapy (Wolfe et al. 2004, Gajewska et al. 2013) or physical training (Balagopal et al. 2010, Gajewska et al. 2013) demonstrated increased sOBR levels, indicating the restoration in leptin sensitivity. Taken together, these studies implicate that manipulating sOBR levels may provide a therapeutic approach for rescue of leptin sensitivity.

Metformin has recently been shown to upregulate hypothalamic expression of OB-Rb in rats (Aubert et al. 2011). Currently, it is unknown whether metformin upregulates peripheral expression of leptin receptors and sOBR levels. Given the fact that liver has a high abundance of leptin receptors (Brabant et al. 2004, Cohen et al. 2005), thus shedding of which produce the majority of plasma sOBR (Maamra et al. 2001, Ge et al. 2002). Therefore, in this study, we tested the effects of metformin on plasma sOBR levels in T2DM patients and mice, and analyzed the expression of major isoforms of leptin receptor in mice liver and kidney, and assessed its effect on hepatosteatosis.

Materials and methods

Patients ethical statement

Informed written consent was obtained from the patients receiving metformin and accepting the collection of blood samples. This study protocol was approved by the Medical Ethics Committee in Xinqiao Hospital, the Third Military Medical University. Twelve newly diagnosed T2DM from May to November in 2013 were included. All of the patients underwent a thorough physical examination and
laboratory evaluation. Those with pregnancy, chronic diseases (cardiovascular, gastrointestinal and respiratory), a history of drug use (antibiotics, steroids, narcotics, antipsychotics, radioactive pharmaceuticals, toxic drugs for medical use and alcoholics), endocrine pathology (Cushing syndrome and hypothyroidism) and recent history of surgery were excluded from the study. These patients were given metformin treatment at 500 mg each time for three times a day (a total of 1500 mg/day) for a month, and then came back for plasma samples collection.

Animal model

All animal experiments were conducted in accordance with the Third Military Medical University guidelines for the care and use of laboratory animals and were approved by the University Animal Care and Use Committee. To set up an animal model with impaired glucose metabolism, C57BL/6 mice, all male, aged 4–6 weeks were randomized into two groups: one set of animals (n = 21) received standard chow diet (CD) and the other set (n = 21) a high-fat (HF) diet. Each group of mice was housed five per cage supplied with a normal rodent diet ad libitum in a pathogen free facility with a 12 h light: 12 h darkness cycle. The mice were gavaged with metformin at 50 mg/kg or 200 mg/kg once a day for a continuous 15 days, with the saline gavaged mice as control as follows: (1) normal chow diet, (2) normal chow diet + metformin (50 mg/kg/day, n = 7); (3) normal chow + metformin (200 mg/kg/day, n = 7); (4) high-fat diet (HF-control, n = 5); (5) high-fat diet + metformin (50 mg/kg/day, n = 6); (6) high-fat diet + metformin (200 mg/kg/day, n = 7). At the end of treatment, mice were fasted overnight before sacrifice, and body weight, FPG, FINs, HOMA-IR and sOB-R levels were determined.

Biochemical assays

The blood samples from animals and patients were immediately put on ice, and plasma was centrifuged with EDTA-containing tubes at 1200 g for 10 min at 4°C. The plasma was spun again at 1200 g for 10 min at 4°C, and the recovered plasma was stored in aliquots at −70°C. The EDTA-plasma was analyzed for glucose, insulin, total leptin (RIA; Linco Research) and sOB-R (ELISA; Diagnostic Systems Laboratories, Webster, TX, USA).

Insulin sensitivity assessment

Glucose and insulin tolerance tests were performed to assess the in vivo insulin sensitivity as we have described previously (Miao et al. 2014). Briefly, the mice were fasted overnight, and then given an i.p. injection of glucose (Sigma) (2 g/kg body weight) in intraperitoneal glucose tolerance test (IPGTT) or an i.p. injection of insulin (Nanjing Pharmaceutical Co., China) (0.5 U/kg body weight) in insulin tolerance test (ITT). Blood samples were drawn from the tail vein immediately before the challenge, as well as 30, 60 and 120 min thereafter. HOMA-IR was used as an index of insulin resistance. HOMA-IR was calculated using the standard formula: fasting glucose (mmol/L) × FINs (μU/L)/22.5.

RNA isolation and real-time quantitative PCR

Total RNA were extracted from each mouse liver using the RNAout reagent (TIANDZ Co., China) according to the manufacturer’s protocol. The reverse transcription was performed using M-MLV reverse transcription kit (Invitrogen), as described previously (Miao et al. 2014). Real-time quantitative polymerase chain reaction (PCR) was performed with an Applied Biosystems PRISM 7500 Sequence Detector (Applied Biosystems), using the IQ™SYBGreen Supermix (Bio-Rad Laboratories). The primers used are listed in Table 1. The PCR procedure was heat at 94°C for 5 min followed by 40 cycles of 95°C for 15 s, 60°C 30 s and 72°C 30 s. The level of the designated gene expression was expressed as the ratio of this gene relative to mouse β-actin levels using the formula of 2−ΔΔCt.

Western blotting analysis

Liver samples from experimental mice were processed to protein extraction and analyzed by Western blot. Antibodies against sheddase ADAM 10 (A disintegrin and metalloproteinase 10) and ADAM17 were incubated at 4°C overnight, followed by washing 5 min for three times with TBST (0.05% Tween 20 in Tris-buffered saline, TBS) and incubation with horseradish peroxidase-conjugated secondary antibody (Zhongshan company Co, Beijing, China) for 2 h at room temperature. The membranes were

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Table 1  Real-time PCR primers for detection of leptin receptors and their shedding enzymes.

<table>
<thead>
<tr>
<th>Gene</th>
<th>GenBank (Access NO)</th>
<th>Primer (5’ to 3’)</th>
<th>Product (bp)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mice-OB-Rt</td>
<td>NM_001032819.1</td>
<td>Forward: CAACACTGAAGGGAAGACACT</td>
<td>79</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse: CACTCTGTCCCAAGTTTACA</td>
<td></td>
</tr>
<tr>
<td>Mice-OB-Ra</td>
<td>U49106.1</td>
<td>Forward: AATGACCGAGGCTGTATGT</td>
<td>194</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse: ATGGACTGTGTTGGAAAGTTTG</td>
<td></td>
</tr>
<tr>
<td>Mice-OB-Rb</td>
<td>U49107.1</td>
<td>Forward: TGCTTTTGACTGTTAGGCA</td>
<td>138</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse: CTGTGCGTGAAACAGGTTTG</td>
<td></td>
</tr>
<tr>
<td>Mice-OB-Rc</td>
<td>U49108.1</td>
<td>Forward: CAAGCAGCAAGATACGGCAG</td>
<td>133</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse: GTGACCTTTTGGAATTCAGTCTG</td>
<td></td>
</tr>
<tr>
<td>Mice-OB-Rd</td>
<td>U49109.1</td>
<td>Forward: ACGCAGGCGTATGTCACTT</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse: TCTTTTGAAATGCTGCTATT</td>
<td></td>
</tr>
<tr>
<td>Mice-Adam10</td>
<td>NM_007399.3</td>
<td>Forward: TGGCGAGGAGAAGGACCC</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse: CTTTCAGCAGAGGTTGCC</td>
<td></td>
</tr>
<tr>
<td>Mice-Adam17</td>
<td>NM_009615.6</td>
<td>Forward: GTGCTGGAGAGATACACCTCC</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse: CACCACCTCTCTGGGAACCC</td>
<td></td>
</tr>
<tr>
<td>Mice-β-actin</td>
<td>NM_007393.3</td>
<td>Forward: CGTCCTGATGTCCTTC</td>
<td>218</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse: ATGTCACGCACGATTCCC</td>
<td></td>
</tr>
</tbody>
</table>

washed again as described above, and the bands were detected by chemiluminescence for visualization. β-actin was used as an internal control.

Liver morphological analysis

Small pieces of liver were fixed in a freshly prepared 4% paraformaldehyde in 0.1 M phosphate buffer and processed into paraffin sections for hematoxylin and eosin staining and histopathological observation. The morphological changes of liver tissues were observed by two pathologists who were blinded from the experimental information.

Liver triglycerides assay

Quantitative analysis of liver TG content was performed by saponification of liver in ethanolic KOH. After neutralization with MgCl₂, TG levels were measured by a colorimetric method (Zhejiang Dongou Biotechnical Company, China) according to the manufacturer’s instruction.

ELISA assay for sOB-R

ELISA analysis of plasma sOB-R levels using a mouse or human sOB-R ELISA kit (Huijia biotechnology, China) was carried according to manufacturer’s instructions. This ELISA kit detects sOB-R and other OB-R molecules that contain the ectodomain of OB-R.

Statistical analysis

All results are expressed as the mean ± S.E.M. Data were analyzed using a one-factor analysis of variance to compare the means of all groups. Between-two group differences in continuous variables were assessed by a univariate analysis with Student’s t-test. One-way ANOVA was used for the comparison of more than two groups, followed by Turkey-Kramer post hoc test. P-value <0.05 was considered to indicate statistical significance.

Results

Metformin increases plasma soluble leptin receptor levels in humans and mice

To detect the effects of metformin therapy on sOB-R levels, the plasma samples from newly diagnosed T2DM patients were tested before and after metformin (1500 mg/day) for 1 month. As shown in Table 2, FPG, FINs, glycated albumin and leptin levels were significantly decreased, whereas sOB-R levels significantly increased in patients after metformin treatment compared with pretreatment values.

To investigate this drug effect in greater detail, we turned to metabolic-disturbed animal model by feeding mice with HF for 5 months. As shown in Fig. 1, HF-induced elevated FPG levels (Fig. 1B), insulin resistance index HOMA-IR (Fig. 1D), impaired glucose tolerance (Fig. 1E) and insulin tolerance (Fig. 1F) were compared with CD-fed mice, whereas, body weight (Fig. 1A) and FINs (Fig. 1C) were not significantly changed. These data demonstrate the presence of HF-induced metabolic disturbance.

Metformin was then administrated at a low (50mg/kg/day) or high dose (200mg/kg/day) for a
consecutive 15 days. Results showed that treatment with this drug significantly decreased FPG (Fig. 2A), HOMA-IR (Fig. 2B) and improved glucose tolerance (Fig. 2E) in HF mice, while showed no significant effects in CD mice (Fig. 2A, B and D). Interestingly, serum sOBR levels significantly increased in both CD and HF mice with metformin treatment, and in a dose-dependent manner (Fig. 2C).

Metformin upregulates leptin receptor expression in liver, but not in kidney

Given the evidence from in vivo radioactive ligand-binding assay that more than 80% of leptin was bound in liver, and 17% of which in kidney (Brabant et al. 2004), we thus detected the expression of leptin receptors in the two organs. Results showed that total leptin receptor

<table>
<thead>
<tr>
<th>Variable</th>
<th>Before drug use</th>
<th>After drug use</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>12</td>
<td>12</td>
<td>NS</td>
</tr>
<tr>
<td>Demography</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (year)</td>
<td>56.15±9.48</td>
<td>56.15±9.48</td>
<td>NS</td>
</tr>
<tr>
<td>Sex (no)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>6</td>
<td>6</td>
<td>NS</td>
</tr>
<tr>
<td>Male</td>
<td>6</td>
<td>6</td>
<td>NS</td>
</tr>
<tr>
<td>BMI (kg/m^2)</td>
<td>23.96±4.14</td>
<td>23.52±3.08</td>
<td>NS</td>
</tr>
<tr>
<td>Waist circumference (cm)</td>
<td>83.77±11.31</td>
<td>83.48±10.59</td>
<td>NS</td>
</tr>
<tr>
<td>Hip circumference (cm)</td>
<td>97.54±10.78</td>
<td>96.79±10.63</td>
<td>NS</td>
</tr>
<tr>
<td>Waist-to-hip ratio</td>
<td>0.86±0.08</td>
<td>0.86±0.06</td>
<td>NS</td>
</tr>
<tr>
<td>Metabolism</td>
<td></td>
<td></td>
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<tr>
<td>Fasting plasma glucose (mmol/L)</td>
<td>7.03±0.90</td>
<td>6.11±0.73</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Fasting plasma insulin (μU/mL)</td>
<td>13.84±6.04</td>
<td>11.16±5.03</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Cholesterol levels (mmol/L)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.10±0.95</td>
<td>3.90±1.31</td>
<td>NS</td>
</tr>
<tr>
<td>LDL</td>
<td>2.99±0.52</td>
<td>2.88±0.57</td>
<td>NS</td>
</tr>
<tr>
<td>HDL</td>
<td>1.32±0.28</td>
<td>1.30±0.25</td>
<td>NS</td>
</tr>
<tr>
<td>Triglycerides (mmol/L)</td>
<td>1.58±0.72</td>
<td>1.50±0.76</td>
<td>NS</td>
</tr>
<tr>
<td>Uric acid (μmol/L)</td>
<td>334.08±60.34</td>
<td>321.96±67.64</td>
<td>NS</td>
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<td>Biomarker</td>
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<tr>
<td>HbAlc (%)</td>
<td>6.86±1.90</td>
<td>6.68±1.80</td>
<td>NS</td>
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<tr>
<td>Glycated albumin</td>
<td>18.04±5.47</td>
<td>15.15±5.77</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Soluble leptin receptor (ng/mL)</td>
<td>15.82±1.71</td>
<td>31.08±6.78</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Leptin (ng/mL)</td>
<td>41.47±4.47</td>
<td>24.03±1.94</td>
<td>&lt;0.05</td>
</tr>
</tbody>
</table>

Plus–minus values are mean ± s.e.m. The body mass index (BMI) is the weight in kilograms divided by the square of the height in meters. HbAlc, glycosylated hemoglobin; NS, not significant.
Metformin upregulates OB-R lowering steatosis

Metformin significantly upregulates the expression of leptin receptors in liver, but not in kidney. The mRNA levels of both long and short leptin receptor isoforms were determined, in the absence or presence of metformin treatment, by real-time PCR using β-actin as an internal control in liver and kidney from CD or HF mice: (A) total leptin receptor (OB-Rt); (B) OB-Rb; (C) OB-Ra; (D) OB-Rc; (E) OB-Rd. The values are mean ± s.e.m. *P<0.05 and **P<0.01.

Figure 3

Metformin does not affect the expression of ADAM10 and ADAM17

Two metallopeptases, ADAM 10 (A disintegrin and metalloproteinase 10) and ADAM17, are reported to participate in enzymatic cleavage of this receptor (Schaab et al. 2012). We detected the effect of metformin on ADAM 10 and ADAM17 expression in liver and kidney. Results showed no significant changes in the mRNA (Fig. 4A and B) or protein levels (Fig. 4C) of both enzymes in liver or kidney (data not shown) before or after metformin treatment.

Figure 4

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Figure 4

Metformin improved glucose metabolism in mice fed a high-fat diet. Effects of metformin for 15 days at designated concentration on male mice: (A) FPG; (B) HOMA-IR; (C) sOB-R levels and its effect on glucose disposal ability at 200 mg/kg/day; (D) IPGTT in CD mice and (E) IPGTT in HF mice. *P<0.05 and **P<0.01.

Figure 2

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Metformin improved glucose metabolism in mice fed a high-fat diet. Effects of metformin for 15 days at designated concentration on male mice: (A) FPG; (B) HOMA-IR; (C) sOB-R levels and its effect on glucose disposal ability at 200 mg/kg/day; (D) IPGTT in CD mice and (E) IPGTT in HF mice. *P<0.05 and **P<0.01.
Effect of metformin on liver triglyceride contents and lipogenic gene expressions

We have previously shown in HepG2 cells that ectopic expression of OB-Rb markedly increased leptin signaling activity (Gan et al. 2012), function of which determines hepatic TG accumulation (Fishman et al. 2007). Therefore, we tested TG and cholesterol contents and observed the morphological changes before and after metformin treatment. Histological staining showed that HF induced extensive lipid droplets in hepatocytes (Fig. 5A2), compared with the chow diet mice (Fig. 5A1), and metformin treatment reduced hepatic steatosis (Fig. 5A4 and A6). In consistence, hepatic TG (Fig. 5B) are increased by HF, levels of which are significantly decreased after metformin treatment and with a greater reduction at higher drug dose. Real-time PCR showed that metformin significantly decreases the expression of SREBP-1c (Fig. 5C) and its target lipogenic genes FAS (Fig. 5D) and ACC-1 (Fig. 5E), whereas carnitine palmitoyltransferase-1 (CPT-1) did not show significant change (data not shown).
Discussion

We hereby demonstrated that metformin upregulates plasma sOBR-R levels in mice and T2DM patients. This is likely due to metformin-stimulated hepatic expression of leptin receptor, especially the short isoforms (OB-Ra, -Rc and -Rd). The stimulation effect is dose-dependent regardless of diet types (CD or HF) in mice. Long isoform OB-Rb can also be upregulated by metformin yet at a higher dose. Our findings that metformin treatment increases hepatic leptin receptors and sOBR-R levels are new and underscore metformin as leptin sensitizer in liver.

There is numerous evidence showing the beneficial effects of metformin on improving NAFLD phenotypes. The main molecular mediator of these effects is regarded as adenosine monophosphate-activated protein kinase (AMPK) (Browning & Horton 2004, Woo et al. 2014, Zheng et al. 2015). By activation of AMPK, metformin improved hepatic lipid metabolism via decreasing activities of ACC-1 and hydroxymethylglutaryl-coenzyme A (HMG-CoA) reductase, promoting β-oxidation, and inhibiting SREBP 1-c, a master transcription factor that induces the expression of lipogenic genes including FAS (Li et al. 2011), leading to decreased steatosis levels. In this study, we have shown that metformin upregulates hepatic OB-Rb, suggesting metformin may directly enhance hepatic leptin sensitivity, an action that may contribute to its antisteatotic effects, especially in the context of obesity.

Indeed, leptin is shown to play a major role in deposition of TG in liver. In the absence of functional leptin (ob/ob) or its receptor (db/db), mice displayed substantial hepatic steatosis, and leptin replacement or re-expression of leptin receptor in the livers of leptin receptor-deficient Zucker diabetic fatty (ZDF) rats reversed this pathology (Lee et al. 2001). Administration of leptin markedly decreases hepatic TG content (by 63%, P<0.05) in normal rats, whereas this effect was abolished in ZDF rats (Fishman et al. 2007). Importantly, mice with ablated hepatic leptin signaling had increased lipid accumulation in the liver (Huynh et al. 2010). Therefore, our result showed that upregulation of hepatic OB-Rb expression under higher metformin dose (200 mg/kg/day) (Fig. 3B) is associated with a further reduction in TG content (Fig. 5B) compared with lower dose of metformin (50 mg/kg/day) and suggests that enhanced leptin sensitivity may contribute to the this antisteatotic effect. In support, expression of lipogenic genes FAS and ACC-1 shows a further decrease under this condition (Fig. 5D and E). Although we did not definitely assess signaling pathways downstream of OB-Rb in mediating the lipid-lowering effects in liver, reports indicate that AMPK and signal transducer and activator of transcription 3 (STAT3) are two pathways likely to be involved. In a recent report, adenovirus-mediated liver-specific OB-Rb overexpression has been shown to activate AMPK pathway to reduce lipid synthesis and promote lipid oxidation and eventually resulted in apparent amelioration of hepatosteatosis in mice under HF conditions (Yoshino et al. 2014). Meanwhile, a number of studies showed that deficiency in STAT3, a major signaling pathway downstream of OB-Rb, or its upstream gp130 in hepatocytes exacerbates fatty liver induced by a choline-deficient, ethionine-supplemented diet (Kroy et al. 2010), alcohol-containing diet (Horiguchi et al. 2008) or high-fat diet (Inoue et al. 2004), whereas overexpression of constitutively activated STAT3 ameliorates high-fat diet-induced fatty liver via inhibition of SREBP-1c (Inoue et al. 2004, Kinoshita et al. 2008). Future studies are thus required to clarify the physiological functions of AMPK and STAT3 pathways downstream of leptin/OB-Rb in mediating the antisteatotic effects of metformin in liver.

In this study, we have shown that metformin significantly increases sOBR-R levels, an effect likely resulted from the increased expression and substrate availability of hepatic leptin receptors (OB-Ra, -Rb, -Rc and -Rd). This is in full agreement with the notion that liver is the main source of plasma sOBR (Cohen et al. 2005). Currently, the biological impact of increased sOBR-R levels is still under dispute, due to a comparable binding affinity of leptin to sOBR and its membrane receptor (Lammert et al. 2001). As a consequent, sOBR-R may modulate leptin function in bidirectional ways: (1) either as an antagonist by its direct competition for the ligand with its specific membrane receptors (Zastrow et al. 2003; Zhang & Scarpace 2009) and inhibits leptin transport into the brain (Tu et al. 2008) (2) or as an agonist, via binding leptin, decreases its clearance in circulation and increases its half-life and function (Gavriloova et al. 1997). Accumulating data favor the view that elevated levels of sOBR is a beneficial biomarker for enhanced leptin sensitivity, which is generally associated with energy surplus condition as in obesity. Worth to mention is that increased plasma sOBR levels are also frequently associated with energy-deficient conditions, as is the case for fasting (Chan et al. 2002), food deprivation (Cohen et al. 2005), type 1 diabetes (Kratzsch et al. 2004, Kratzsch et al. 2006), eating disorders such as anorexia nervosa and bulimia nervosa (Monteleone et al. 2002) or catabolic states as in nephritic syndrome.
(Schroth et al. 2003) and severe malnutrition (Stein et al. 2006). In such conditions, the increased sOBR levels are generally regarded as a compensatory mechanism by which leptin action is antagonized; hence, food intake is promoted and energy consumptions decreased, so as to replenish the body’s energy shortage. Here, our data suggest that increased sOBR levels by metformin did not show an enhanced central leptin sensitivity, as our data exhibit no significant reduction in body weight in both mice (data not shown) and T2DM patients (Table 2). This is in discrepancy with previous report where sOBR transgenic mice demonstrated enhanced leptin sensitivity as shown by lower body weight, increased energy expenditure and lower body fat content compared with wild-type mice (Lou et al. 2010). One explanation for this discrepancy may be because the patients who receive metformin treatment and come back for blood testing are not obese (BMI 21.41 ± 1.386) (Table 2), although their body weight, waist circumference and waist-to-hip ratio show a tendency of decrease (Table 2), yet not reach a statistical significance. The second explanation may be because the therapeutic time using metformin (1 month in patients and 15 days in mice) may not be long enough to show a distinguishable weight-loss effect. Further studies are required to determine the dose and time effects of metformin on leptin sensitivity in central and peripheral tissues, and should include patients with different degree of obesity.

Worth to mention, it is possible that when combined with additional endocrine abnormalities, the effect of metformin on leptin receptor expression and plasma sOBR levels may be absent or over-ridden. As has been reported previously, 4 months therapy with metformin (1500mg daily) in seven obese women with hyperinsulinemia and PCOS did not affect the sOBR levels (Romualdi et al. 2008). It is possible that in the presence of high circulating levels of other hormones, metformin-stimulated signaling pathways are blunted and other regulatory mechanisms become more prominent. Hence, the mechanisms underlying metformin-stimulated leptin receptor gene expression warrant further investigation.

In conclusion, the findings that metformin increases sOBR levels and hepatic leptin receptors including OB-Rb implicate enhanced hepatic leptin sensitivity as an underlying mechanism, mediating its antisteatotic effect. Our study expands current understanding of metformin as leptin sensitizer not only in the brain (Aubert et al. 2011) but also in liver, results of which may provide novel rationale in future clinical uses of metformin in leptin resistance-associated disorders.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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Author contribution statement
Xuemei Tang, Jingwen Li, Wei Xiang and Ye Cui conducted the experiments, analyzed the data and drew graphs. Bin Xie, Xiaodong Wang and Zihui Xu contributed to discussion and revised the paper. Lixia Gan designed experiments, wrote the manuscript and takes full responsibility for the present work.

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