The estrogen receptor α-selective agonist propyl pyrazole triol improves glucose tolerance in ob/ob mice; potential molecular mechanisms

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Abstract

The aim of this study was to validate the role of estrogen receptor α (ERα) signaling in the regulation of glucose metabolism, and to compare the molecular events upon treatment with the ERα-selective agonist propyl pyrazole triol (PPT) or 17β-estradiol (E2) in ob/ob mice. Female ob/ob mice were treated with PPT, E2 or vehicle for 7 or 30 days. Intraperitoneal glucose and insulin tolerance tests were performed, and insulin secretion was determined from isolated islets. Glucose uptake was assayed in isolated skeletal muscle and adipocytes. Gene expression profiling in the liver was performed using Affymetrix microarrays, and the expression of selected genes was studied by real-time PCR analysis. PPT and E2 treatment improved glucose tolerance and insulin sensitivity. Fasting blood glucose levels decreased after 30 days of PPT and E2 treatment. However, PPT and E2 had no effect on insulin secretion from isolated islets. Basal and insulin-stimulated glucose uptake in skeletal muscle and adipose tissue were similar in PPT and vehicle-treated ob/ob mice. Hepatic lipid content was decreased after E2 treatment. In the liver, treatment with E2 and PPT increased and decreased the respective expression levels of the transcription factor signal transducer and activator of transcription 3, and of glucose-6-phosphatase. In summary, our data demonstrate that PPT exerts anti-diabetic effects, and these effects are mediated via ERα.

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Introduction

The metabolic syndrome, defined by central obesity, hyperglycemia, decreased high-density lipoprotein, cholesterol, elevated triglycerides (TGs) and blood pressure, has become a major public health challenge worldwide (Zimmet et al. 1998, Crespo et al. 2002). Changes in environment and lifestyle have escalated the rates of type 2 diabetes and obesity (Zimmet et al. 2005). Estrogen deficiency in postmenopausal women contributes to the development of visceral obesity, insulin resistance and the risk of developing type 2 diabetes (Louet et al. 2004), while treatment with 17β-estradiol (E2) or conjugated equine estrogens improves insulin sensitivity and lowers blood glucose levels (Espeland et al. 1998, Crespo et al. 2002, Saglam et al. 2002). Results from the Women’s Health Initiative study showed a reduced incidence of diabetes in postmenopausal women on hormone replacement therapy or after estrogen treatment alone (Margolis et al. 2004, Bonds et al. 2006). Moreover, hormone replacement therapy in postmenopausal women with coronary artery disease resulted in a 35% reduction in the incidence of type 2 diabetes at the 4-year follow-up (Kanaya et al. 2003).

Estrogen signals via binding to either of two estrogen receptors (ERs), ERα and ERβ (Dahlman-Wright et al. 2006). ERs belong to the nuclear receptor family of ligand-activated transcription factors, and modulate the expression of target genes by binding either to classic estrogen response elements or to other transcription factors, which then bind to their respective response elements. The two ERs show overlapping, yet distinct, patterns of expression (Dahlman-Wright et al. 2006). Of particular relevance for glucose homeostasis, ERα is the major ER expressed in the liver (Kuiper et al. 1997), adipose tissue (Lundholm et al. 2004), skeletal muscle (Wiik et al. 2003), and pancreatic islets (Geisler et al. 2002). ER subtype-specific ligands have been developed, and are increasingly used to further clarify the specific roles of ERα and ERβ (Dahlman-Wright et al. 2006). For example, the ERα-selective ligand propyl pyrazole triol (PPT) is...
reported to have a 410-fold selectivity for ERα versus ERβ (Stauffer et al. 2000). An in vivo study using this compound shows effects similar to those of E2, including increased uterine weight, and prevention of increased body weight and reduced bone mineral density normally associated with ovariectomy (Harris et al. 2002).

Estrogen deficiency also contributes to the development of obesity, insulin resistance, hyperglycemia, and type 2 diabetes in rodents (Louet et al. 2004). Accordingly, ovariectomy increased body weight, basal glucose levels and caused impaired glucose tolerance (in mice (Bailey & Ahmed-Sorour 1980). Furthermore, aromatase knockout (ARKO) mice, which possess a genetic impairing in endogenous estrogen synthesis, exhibit decreased glucose tolerance, insulin resistance, and increased adiposity (Jones et al. 2000, Takeda et al. 2003). To investigate whether the above effects of estrogens are mediated via ERα or ERβ, isoform-specific knockout animals were studied. These studies provided evidence that ERα knockout (ERKO) mice, but not ERβ knockout (BERKO) mice, exhibit metabolic effects similar to those observed in ovariectomized and ARKO mice, suggesting a critical role for ERα in the metabolic effects of estrogen (Heine et al. 2000).

We have recently demonstrated that glucose intolerance in ERKO mice is mainly due to hepatic insulin resistance, which was accompanied by the up-regulation of genes regulating fatty acid synthesis in the liver (Bryzgalova et al. 2006). Long-term treatment with E2 (30 days) improved glucose tolerance, insulin sensitivity and the insulin response to glucose in vivo in diabetic ob/ob mice (Gao et al. 2006). The expression of lipogenic genes in the livers of ob/ob mice was down-regulated following estrogen treatment, and this was accompanied by reductions in liver TG levels (Gao et al. 2006). Additional studies demonstrated that the signal transducer and activator of transcription 3 (Stat3) could be a mediator of the effects of estrogen on lipogenic gene expression (Gao et al. 2006).

Our above studies in ERKO and ob/ob mice are consistent with a critical role for ERα in the estrogen-mediated improvement in glucose tolerance. The aim of the present study was to further investigate the molecular mechanisms behind the anti-diabetic effects of estrogens. For this purpose, we compared the molecular events associated with improved glucose tolerance in ob/ob mice following treatment with E2 and PPT.

Materials and Methods

Animals

All animal experiments were approved by the local ethical committees. E2 was purchased from Sigma and was used as a reference substance. The ERα-selective agonist PPT was obtained from Karo Bio (Huddinge, Sweden, 7 or 30 days treatment, single dose) or purchased from Tocris Bioscience (Ellisville, MO, USA, 30 day multiple doses and 2–6 h treatment). Three-month old female ob/ob mice bred in our own colony and in Umeå University, Sweden, were used for the experiments. Animals were treated subcutaneously either with E2 (0·005, 0·05, and 0·1 mg/kg body weight per day) or PPT (0·1, 1·0, and 2·5 mg/kg body weight per day) for 7–30 days. For the short-term study, female C57BL/6 mice were ovariectomized to remove the major site of endogenous estrogen synthesis at 10 weeks of age and killed at 14 weeks of age, 2, 4, or 6 h after a single treatment (5 mg/kg body weight). Mice were injected subcutaneously. A group of ERKO mice and matched controls (obtained from Taconic, Ry, Denmark) were treated for 7 days with PPT (1 mg/kg, body weight). PPT was dissolved in 90% sesame oil and 10% ethanol, and control animals received vehicle. Blood was collected, centrifuged at 12 000 g for 2 min, and plasma was stored at −80 °C for expression studies.

Intraperitoneal glucose tolerance test (IPGTT)

After 7–30 days of treatment, animals were fasted overnight and blood glucose levels were determined. The animals were administered with glucose solution (2 g/kg body weight) by i.p. injection, and blood glucose concentrations were measured at 10, 30, 60 and 120 min after glucose load. Blood glucose levels were measured using a MediSence glucose analyzer (Abbot Scandinavia AB).

Intraperitoneal insulin tolerance test (IPITT)

For IPITT experiments, blood glucose was measured in overnight fasted animals and insulin was injected at a dose of 0·25 U/kg body weight. Ten minutes later, glucose was injected at a dose of 1 g/kg body weight and blood glucose concentrations were measured at 15, 30, 60, 90, and 120 min after the glucose load.

Insulin secretion in vitro

Pancreatic islets were isolated by collagenase digestion (Khan et al. 1995). Groups of five islets were preincubated at 37 °C for 1 h in Krebs–Ringer bicarbonate buffer (KRB), pH 7·4, containing 3·3 mmol/l glucose. The islets were then incubated in KRB for 1 h at 37 °C with 3-3 or 16·7 mmol/l glucose, or with 3·3 mmol/l glucose and 20 mmol/l arginine. After incubation, the supernatants were stored at −20 °C prior to insulin assay. Insulin was measured by RIA (Herbert et al. 1965).

Glucose uptake in skeletal muscle

Mice were anesthetized by i.p. injection of 2·5% avertin (0·02 ml/g body weight), and the extensor digitorum longus (EDL) and soleus muscles were removed for in vitro incubation. Isolated muscles were incubated for glucose
uption as described for the rat epitrochlearis muscle (Wallberg-Henriksson et al. 1987), in the absence or presence of insulin (0·18 or 12 nM) for 30 min. Glucose transport was assessed using 2-deoxyglucose (Hansen et al. 1995). Calculations included determination of the extracellular space and intracellular 2-deoxyglucose concentrations (Wallberg-Henriksson et al. 1987, Hansen et al. 1995). Glucose transport activity is expressed as μmol/ml 2-deoxyglucose per hour. A more detailed description of the method is given in the Supplementary Information.

Glucose uptake in adipose tissue

Adipocytes were isolated from mice by collagenase digestion as described (Arner & Engfeldt 1987), and incubated at a concentration of 3·5% (vol/vol) in Krebs–Ringer phosphate buffer (pH 7·4) containing albumin (40 mg/ml), (3–3H) glucose (5 × 10^6 c.p.m./ml), unlabelled glucose (1 μmol/l) and various concentrations of human insulin (0, 10^{-15}–10^{-8} M). After 2 h at 37°C using air as the gas phase, incubations were stopped by rapidly chilling the incubation vials to 4°C and adding 50 μl 6 M H2SO4. Incorporation of radiolabeled glucose into adipocyte lipids was assayed.

Metabolomics of lipid-soluble liver tissue extract using 1H nuclear magnetic resonance (NMR) spectroscopy

Lipid-soluble liver tissue extracts were prepared and the amounts of lipids were analyzed using NMR spectroscopy, as described in the Supplementary Information.

RNA preparation and microarray analysis

Total RNA was prepared from frozen tissue using TRIZol Reagent (Invitrogen) and purified using RNeasy Mini Kits (Qiagen). RNA quality was assayed using an Agilent 2100 Bioanalyzer (Agilent, Palo Alto, CA, USA). RNA was prepared for microarray analysis and hybridized to Mouse Genome 430 2.0 arrays according to the Affymetrix GeneChip Expression Analysis manual (Affymetrix, Santa Clara, CA, USA). For the first set of microarray data (dataset I), RNA from each treatment group was pooled (n = 5) before preparation of probes. For the second set of microarray data (dataset II), RNA from individual mice (n = 3) was analyzed.

Bioinformatics

Output files from microarray analyses were analyzed using Affymetrix GeneChip operating software (GCOS). To assess differential gene expression between the PPT treatment and control groups, Affymetrix algorithms in GCOS was used for dataset I. For dataset II, the Bioconductor program (www.bioconductor.org) for R was used with the AffylinGUI linear modeling Graphical User Interface (affylmGUI) package (Wettenhall et al. 2006), which is based on linear models and empirical Bayes methods (Smyth 2004). Data were normalized using the robust multiarray average background correction method (Irizarry et al. 2003), and adjusted using the Benjamini & Hochberg (1995) method for controlling false discovery rate. For Tables 2 and 3, only genes with reliable detection levels on all arrays (present) are included.

Real-time PCR analysis

RNA from individual animals was reverse transcribed into cDNA using Superscript II (Invitrogen) or Reverse Transcription Reagents (Applied Biosystems, Foster City, CA, USA) with random hexamer primers. Analyses were performed using a 7500 Fast Real-Time PCR System with Power SYBR Green Reagents (Applied Biosystems). PCR products were further analyzed by melting curve analysis to confirm single products. mRNA levels were normalized to hypoxanthine ribosyltransferase mRNA levels. Primer sequences are provided in the Supplementary Information.

Western blot analysis

Liver protein extracts were prepared and equal amounts of protein were separated by electrophoresis. Membranes were probed using Stat3 (Thermo Scientific, Cheshire, UK), phospho-Stat3 (Tyr705, Cell Signaling Technology, Danvers, MA, USA) and glucose-6-phosphatase (C-14, Santa Cruz Biotechnology, Santa Cruz, CA, USA) antibodies, and band densities were quantified using ImageJ (Rasband 1997–2007). A more detailed description of the method is given in the Supplementary Information.

Statistical analysis

Results are reported as mean ± s.e.m. Statistical differences were determined by an unpaired Student’s t-test (Figs 1, 3–6, 10 and 11) or one-way ANOVA (Kirkman 1996) followed by Fisher’s least significant difference post hoc analysis (Figs 2, 7 and 9, Table 1). Statistical significance was accepted for P < 0·05. Statistical analyses for the microarray data are included in the Bioinformatics section.

Results

PPT improves glucose tolerance and decreases fasting blood glucose

ob/ob mice were treated with PPT, E2 or vehicle. A treatment of 7 days with either PPT (1 mg/kg) or E2 (0·1 mg/kg) had no effect on body weight when compared between treatment groups (51·10 ± 0·94 g, 51·66 ± 0·89 g, and 52·33 ± 1·08 g for PPT, E2, and vehicle treatment respectively). After overnight fasting, blood glucose concentrations were similar in mice treated for 7 days with vehicle, PPT or E2 (Fig. 1a).
IPGTT, however, revealed that PPT and E2 markedly improved glucose tolerance. To investigate whether long-term treatment alters basal glucose levels, ob/ob mice were treated for 30 days with the same doses of PPT or E2. Fasting blood glucose was significantly decreased in PPT and E2-treated animals, and glucose tolerance was markedly improved (Fig. 1b). A tendency toward increased body weight during the course of the experiment in vehicle-treated animals was not seen in E2-treated animals (Table 1). However, this did not reach statistical significance.

To investigate the dose–response of the observed effects of PPT, ob/ob mice were treated with PPT at different concentrations for 30 days. Basal blood glucose concentrations were significantly decreased in animals treated with 0.1, 1.0, or 2.5 mg/kg of PPT (Fig. 2a), while glucose tolerance was significantly improved at doses of 1.0 and 2.5 mg/kg PPT. At doses of 0.005, 0.05, and 0.1 mg/kg, E2 similarly improved fasting blood glucose levels and glucose tolerance after 30 days of treatment (Fig. 2b).

**PPT improves insulin sensitivity**

In the insulin tolerance test, fasting blood glucose levels were similar in control, PPT- and E2-treated mice after 7 days (Fig. 3a). Blood glucose concentrations increased in all mice after the glucose challenge (15 min), although the increase in blood glucose was significantly less in PPT and E2-treated mice. Blood glucose concentrations then gradually dropped in all groups and were significantly lower in PPT and
E2-treated mice, compared with control mice, at the 60, 90, and 120 min time points.

Thirty days' treatment of ob/ob mice with either PPT or E2 significantly decreased fasting blood glucose levels (Fig. 3b). Blood glucose levels were then significantly reduced throughout the experiment in mice treated with either PPT or E2, compared with mice treated with vehicle (Fig. 3b).

**The effect of PPT is mediated via ERα**

Seven days of PPT treatment (1 mg/kg body weight) in ERKO mice had no effect on either glucose tolerance (Fig. 4a) or insulin sensitivity (Fig. 4b), as measured using IPGTT and IPITT respectively. PPT also had no effect in control mice.

**Skeletal muscle and adipose tissue glucose uptake is unaltered by PPT treatment**

Seven days of PPT treatment (1 mg/kg) was without effect on basal glucose uptake in the skeletal muscle in ob/ob mice.

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**Table 1**  Body weights (mean ± S.E.M.) in ob/ob mice after 30 days of treatment with vehicle, 17β-estradiol (E2; 0.1 mg/kg body weight) and propyl pyrazole triol (PPT; 1 mg/kg body weight)

<table>
<thead>
<tr>
<th>Treatment group</th>
<th>Before treatment (g)</th>
<th>After treatment (g)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>49.27 ± 0.7</td>
<td>52.00 ± 1.64</td>
<td></td>
</tr>
<tr>
<td>E2</td>
<td>49.25 ± 1.13</td>
<td>49.00 ± 0.96</td>
<td>NS</td>
</tr>
<tr>
<td>PPT</td>
<td>50.00 ± 1.40</td>
<td>51.38 ± 1.42</td>
<td>NS</td>
</tr>
</tbody>
</table>

Data are presented as means ± S.E.M.; for all groups, n = 7–8.

E2-treated mice, compared with control mice, at the 60, 90, and 120 min time points.

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**Figure 3** IPITT was performed in overnight fasted ob/ob mice treated with either E2 (open circle; 0.1 mg/kg body weight), PPT (triangle; 1 mg/kg body weight), or vehicle (filled circle) for (a) 7 days (n = 9) or (b) 30 days (n = 7–8). Mice were injected first with insulin at a dose of 0.25 U/kg, i.p., and 10 min later with glucose at the dose 1 g/kg i.p. Blood glucose concentrations were measured at the basal condition, and at different time points after the glucose load. Data are presented as mean ± S.E.M.* *P < 0.05, **P < 0.01, ***P < 0.001 versus vehicle-treated ob/ob mice.

**Figure 4** (a) IPGTT and (b) IPITT in overnight fasted ERKO (triangles) and control (circles) mice treated with vehicle (open circles and triangles) or PPT (1.0 mg/kg body weight; filled circles and triangles) for 7 days. Blood glucose concentrations were measured at the basal state and after glucose load (2 g/kg, i.p.) at the indicated time points. Data are presented as mean ± S.E.M. For IPITT, mice were injected first with insulin at a dose of 0.25 U/kg, i.p., and 10 min later with glucose at the dose 1 g/kg i.p. Blood glucose concentrations were measured at the basal condition, and at different time points after the glucose load. Data are presented as mean ± S.E.M.
Insulin (12 nmol/l) increased 2-deoxyglucose uptake in the soleus and EDL skeletal muscles, but PPT treatment did not affect insulin-stimulated glucose uptake. Furthermore, glucose uptake in adipose tissue was unchanged after 30 days of PPT treatment (Fig. 5c).

**Preserved B-cell secretory capacity after PPT treatment**

Glucose (16.7 mM) induced insulin secretion in isolated islets from both control and PPT-treated ob/ob mice, compared with the basal state (3.3 mM), with no difference between the groups (Fig. 6). Arginine-induced insulin secretion was also similar between control and PPT-treated animals.

**Differential effects of PPT and E₂ on hepatic lipid profiles**

We have previously reported that treatment of ob/ob mice with E₂ decreases liver TGs. NMR analyses of lipid extracts from the livers of ob/ob mice treated with PPT at 0.1, 1.0, and 2.5 mg/kg for 30 days showed no significant effects on total lipids, TGs or cholesterol, while treatment of animals with E₂ at 0.005, 0.05, and 0.1 mg/kg significantly decreased total lipid, TG, and cholesterol levels (Fig. 7).

**Identification of ERα target genes in the liver; comparing the effects of PPT and E₂**

To further characterize the molecular effects of PPT in ob/ob mice, we performed gene expression profiling experiments on livers from PPT- (0.1, 1.0, and 2.5 mg/kg) and vehicle-treated animals (dataset I), with the ultimate goal of comparing these gene expression profiles with those of E₂-treated animals. Expression profiling was conducted at each dose since the absorption, distribution, metabolism, and excretion properties

(Fig. 5a and b). Insulin (12 nmol/l) increased 2-deoxyglucose uptake in the soleus and EDL skeletal muscles, but PPT treatment did not affect insulin-stimulated glucose uptake. Furthermore, glucose uptake in adipose tissue was unchanged after 30 days of PPT treatment (Fig. 5c).
are poorly defined for this compound. Gene expression profiling for all PPT dose groups was initially carried out with pooled RNA. The number of regulated genes increased with dose (Fig. 8a and b). After treatment with 0.1, 1.0, and 2.5 mg/kg body weight, there were 490, 1364, and 1897 increased genes, and 502, 1482, and 1583 decreased genes respectively compared with vehicle. 140 increased and 226 decreased genes were regulated at all investigated doses of PPT treatment (Supplementary Table 1, see Supplementary data in the online version of the Journal of Endocrinology at http://joe.endocrinology-journals.org/content/vol199/issue2/), and there was a dose-dependent increase in the average fold-change for regulated genes (Fig. 8c).

Real-time PCR was used to confirm the changes in expression of several genes that were identified by the microarray analysis. Stat3 and ERα were among the genes that were increased by PPT, whilst the decreased genes included glucose-6-phosphatase, catalytic (G6pc), CCAAT/enhancer-binding
protein β (Cebp b), Krüppel-like factor 15 (Klf15), glucose transporter 1 (Glut1, also called SLC2A1), and very low density lipoprotein receptor (Fig. 9).

By comparing the genes identified as being regulated by E2 from our previous study with those regulated by all doses of PPT (Table 2), we identified gene expression changes that are common to E2 and PPT treatment. Included among these changes are the up-regulation of Stat3 and the down-regulation of G6pc.

To confirm the gene expression profiles found in pooled liver RNA samples, and to facilitate comparison with previous gene expression profiling experiments in E2-treated ob/ob mice in which individual animals were assayed, livers from individual animals treated with PPT (1 mg/kg) were analyzed (dataset II). The gene expression changes shown in Table 3 are conserved between E2 and PPT treatment, using a filter of a two-fold change to identify differentially-expressed genes. Again, G6pc is identified as a gene that is consistently down-regulated after PPT and E2 treatment. The complete list of genes significantly regulated by PPT at 1 mg/kg is included in Supplementary Table 2, see Supplementary data in the online of version of the Journal of Endocrinology at http://joe.endocrinology-journals.org/content/vol199/issue2/.

Changes in Stat3 and G6pc mRNA levels were accompanied by changes in Stat3 and G6pc protein levels

The induction of Stat3 protein and of activated, phosphorylated Stat3 protein (Fig. 10a) were demonstrated in the livers of ob/ob mice after 30 days of PPT treatment (1 mg/kg), though the induction of Stat3 protein did not quite reach statistical significance (Fig. 10b). For glucose-6-phosphatase, a decrease in protein levels was demonstrated (Fig. 10a and b).

G6pc and Stat3 are ERα target genes in liver

To investigate whether G6pc and Stat3 represent direct target genes for PPT, we assayed their expression after short-term PPT treatment in ovariectomized mice. The mRNA for G6pc was significantly decreased after 6 h of PPT treatment (Fig. 11a). The expression of Stat3 was significantly increased from 4 h of PPT treatment (Fig. 11b).

Discussion

In the present study we used leptin-deficient ob/ob mice, an animal model of type 2 diabetes. ob/ob mice become hyperglycemic and hyperinsulinemic from the age of 1–2 months, at which point body weight also starts to increase, compared with wild-type animals (Westman 1968). At 5–6 months of age, the animals reach maximum body weight, which remains stable until 13–17 months of age (Westman 1968). Hyperglycemia and hyperinsulinemia also increase with age, and the highest mean blood glucose and insulin values are obtained in 4–6 month old animals.

We have shown that treatment of 3-month-old female ob/ob mice with E2 for 30 days significantly decreased basal blood glucose levels and improved glucose tolerance and
insulin sensitivity (Gao et al. 2006). The insulin response to glucose in vivo was also significantly improved. In this study, we demonstrate that glucose tolerance and insulin sensitivity are significantly improved in ob/ob mice from 7 days of treatment with E2, which confirms the strong anti-diabetic effect of estrogens.

Chronic estrogen treatment has been shown to decrease food intake and body weight in rodents (Alonso et al. 2006, Clegg et al. 2006, Roesch 2006, Gao et al. 2007, Węgorzewska et al. 2008). In the present study, E2-treated animals did not exhibit the trend toward increased body weight that was seen in controls, although we could not demonstrate a statistical difference in body weight between these groups. However, caution should be employed when making direct comparisons between this and previous studies in this respect, since the effect of E2 on body weight could depend upon factors such as the dose of E2, its route of administration, and the animal model used. For example, reduced weight gain was observed in ob/ob and db/db mice treated with E2 for 4 weeks by s.c. intrascapular capsule implants (Gao et al. 2007). However, neither the dose of E2 nor its circulating levels are discussed in this article, although the latter is described to be high, and so a comparison with the current study is difficult. Decreases in weight gain have also been reported in E2-treated ovariectomized rats with normal leptin signaling (Alonso et al. 2006, Clegg et al. 2006, Roesch 2006, Węgorzewska et al. 2008). In this study, we have treated leptin-deficient female ob/ob mice with s.c. E2 doses that are either comparable or less than those used in the above reports, after normalizing E2 dose for body weight.

The effects that we observe on glucose tolerance and insulin sensitivity following E2 treatment are mediated via ERα, since PPT has effects similar to E2 on glucose metabolism. To further investigate the selectivity of PPT as an ERα-agonist, we treated...
ERKO mice with PPT for 7 days and then performed glucose and insulin tolerance tests. As expected, PPT had no effect on glucose or insulin tolerance in ERKO mice, showing that PPT works as an ERα-selective agonist.

In ob/ob mice, the effect of PPT was dose- and time dependent. Thus, while seven days’ treatment with PPT improved glucose tolerance without decreasing the fasting blood glucose level, treatment of ob/ob mice for 30 days significantly decreased fasting blood glucose and improved glucose tolerance. The present data are consistent with reports suggesting a critical role for ERα in glucose control (Heine et al. 2000, Bryzgalova et al. 2006).

We have previously proposed that hyperglycemia, hyperinsulinaemia, and insulin resistance in ERKO mice are mainly due to impaired insulin sensitivity in the liver (Bryzgalova et al. 2006). Therefore, the improved glucose metabolism in ob/ob mice treated with PPT is likely to occur as a consequence of improved hepatic insulin sensitivity in these animals. This notion is supported by our findings that basal and insulin-mediated glucose uptake in skeletal muscle and adipose tissue of PPT-treated mice were similar to vehicle-treated mice. In addition, the secretory capacity of pancreatic islets was unchanged after PPT treatment.

In contrast to E2-treated mice, the hepatic lipid content of PPT-treated mice was unchanged. Furthermore, the expression of lipogenic genes (e.g., stearoyl-coenzyme A desaturase 1 and fatty acid synthase, data not shown) was not significantly reduced in PPT-treated mice, as previously reported for E2-treated mice (Gao et al. 2006). This suggests that the regulation of lipid metabolism may not be critical for PPT-mediated improvements in glucose tolerance and insulin sensitivity.

To study the molecular mechanisms behind the antidiabetic effect of estrogens, we have analyzed genome-wide expression profiles in the liver from PPT-treated versus vehicle-treated mice. The PPT doses were selected based on previous in vivo studies (Lai et al. 2003). Our study demonstrated a dose-dependent increase in the number of changed genes. We focused on genes that were co-regulated in ob/ob mice upon E2 and PPT treatment respectively. Importantly, the expression of Stat3 was increased by both E2 and PPT (Table 2). In addition, we show that the protein expression and activity of Stat3 were induced after PPT treatment, in accordance with previous data in E2-treated ob/ob mice (Gao et al. 2006). Liver-specific deficiency of Stat3 leads to insulin resistance in mice, whereas the activation of Stat3 signaling by expression of a constitutively active form of Stat3 in the liver improves glucose tolerance and insulin resistance in diabetic db/db mice (Inoue et al. 2004).

Accordingly, we have previously proposed that increased expression of Stat3 in the liver of ob/ob mice upon E2 treatment is a potential mediator of the effects of E2 in enhancing hepatic insulin sensitivity (Gao et al. 2006). Stat3, included in Table 2, is not identified in Table 3 as a gene co-regulated by PPT and E2. This probably reflects the fact that levels of Stat3 expression vary between individuals. In our experience, individual variation within groups must be relatively small in order to obtain significance with methods like affylmGUI, which was used to identify regulated genes as input for this table. Stat3 was significantly (P<0.05) regulated by PPT when assayed by real-time PCR (Fig. 9, n = 5).

A gene co-ordinately decreased by both E2 and PPT treatment was G6pc. The expression of G6pc is high in diabetic animals and contributes to the development of hyperglycemia (Trinh et al. 1998). Over-expression of G6pc in cultured hepatocytes and in rats in vivo results in increased glucose production (Seoane et al. 1997, Trinh et al. 1998). Therefore, decreased expression of G6pc due to PPT and E2 treatment may contribute to the decreased fasting blood glucose levels observed in animals treated with PPT. Two earlier studies in ob/ob mice and aging rats provide evidence for decreased glucose-6-phosphatase activity after estrogen treatment (Borthwick et al. 2001, Moorthy et al. 2004). Interestingly, using the ChIP-on-chip assay, we identified functional binding sites for ERα that could mediate direct regulation around the transcription start site (at +4548 and +208) of the G6pc gene (Gao et al. 2008). In parallel with STAT-3 and G6Pase, the expression of a number of other genes was altered by PPT treatment. Thus, the expression levels of Cebpb, Klf15, Glut1, and Vldir were dose-dependently decreased by PPT treatment.
Interestingly, these genes are known to affect hepatic glucose production and insulin sensitivity (Wang et al. 2000, Croniger et al. 2001, Wood & Trayhurn 2003, Gray et al. 2007).

In conclusion, our data demonstrate that PPT improves glucose tolerance and insulin sensitivity in ob/ob mice. These effects of PPT are due to the activation of ERα signaling and appear to be mediated by Stat3 and G6pc.

Declaration of interest

J-A˚ G is a consultant and share holder of Karo Bio AB. The other authors have nothing to declare.

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Improvement of glucose tolerance by PPT


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