

University of Waterloo

---

From the Selected Works of Daniel Hardy

---

2020

# Addition of olive oil to diet of rats with mild pre-gestational diabetes impacts offspring $\beta$ -cell development

Daniel B Hardy  
Edith J Arany

## RESEARCH

# Addition of olive oil to diet of rats with mild pre-gestational diabetes impacts offspring $\beta$ -cell development

Bushra Taqui<sup>1</sup>, Farzad Asadi<sup>1</sup>, Evangelina Capobianco<sup>2</sup>, Daniel Barry Hardy<sup>3</sup>, Alicia Jawerbaum<sup>2</sup> and Edith Juliana Arany<sup>1</sup>

<sup>1</sup>Lawson Health Research Institute, Department of Pathology and Laboratory Medicine, Schulich School of Medicine and Dentistry, Western University, London, Ontario, Canada

<sup>2</sup>CONICET-Universidad de Buenos Aires, Laboratory of Reproduction and Metabolism, CEFYBO, Buenos Aires, Argentina

<sup>3</sup>Departments of Obstetrics and Gynaecology and Physiology & Pharmacology, Schulich School of Medicine and Dentistry, Western University, London, Ontario, Canada

Correspondence should be addressed to E Arany: [earany@uwo.ca](mailto:earany@uwo.ca)

## Abstract

Maternal diabetes impairs fetal development and increases the risk of metabolic diseases in the offspring. Previously, we demonstrated that maternal dietary supplementation with 6% of olive oil prevents diabetes-induced embryo and fetal defects, in part, through the activation of peroxisome proliferator-activated receptors (PPARs). In this study, we examined the effects of this diet on neonatal and adult pancreatic development in male and female offspring of mothers affected with pre-gestational diabetes. A mild diabetic model was developed by injecting neonatal rats with streptozotocin (90 mg/kg). During pregnancy, these dams were fed a chow diet supplemented or not with 6% olive oil. Offspring pancreata was examined at day 2 and 5 months of age by immunohistochemistry followed by morphometric analysis to determine number of islets,  $\alpha$  and  $\beta$  cell clusters and  $\beta$ -cell mass. At 5 months, male offspring of diabetic mothers had reduced  $\beta$ -cell mass that was prevented by maternal supplementation with olive oil. PPAR $\alpha$  and PPAR $\gamma$  were localized mainly in  $\alpha$  cells and PPAR $\beta/\delta$  in both  $\alpha$  and  $\beta$  cells. Although Ppar $\beta/\delta$  and Ppar $\gamma$  RNA expression showed reduction in 5-month-old male offspring of diabetic rats, Ppar $\beta/\delta$  expression returned to control levels after olive-oil supplementation. Interestingly, *in vitro* exposure to oleic acid (major component of olive oil) and natural PPAR agonists such as LTB<sub>4</sub>, CPC and 15dPGJ<sub>2</sub> also significantly increased expression of all Ppars in  $\alpha$ TC1–6 cells. However, only oleic acid and 15dPGJ<sub>2</sub> increased insulin and Pdx-1 expression in INS-1E cells suggesting a protective role in  $\beta$ -cells. Olive oil may be considered a dietary supplement to improve islet function in offspring of affected mothers with pre-gestational diabetes.

## Key Words

- ▶ diabetes
- ▶ pregnancy
- ▶ olive oil
- ▶ PPARs

*Journal of Endocrinology*  
(2020) **246**, 175–187

## Introduction

The *in utero* environment plays an important role in the development of the fetus and the neonate (Harris *et al.* 2017, Marciniak *et al.* 2017). Pre-gestational

diabetes affects organogenesis and increases the risk of congenital malformations (Correa *et al.* 2008). Moreover, both pre-gestational and gestational diabetes raise the

predisposition to insulin resistance early in life (Catalano *et al.* 2003, Lacroix *et al.* 2013) and the development of type 2 diabetes (Sobngwi *et al.* 2003, Chon *et al.* 2014). In humans, exposure to hyperglycemia *in utero* leads to differential effects on male and female offspring upon the risk of developing diabetes later in life (Sobngwi *et al.* 2003, Mauvais-Jarvis 2018).

It has been shown that not only the quantity (Ojha *et al.* 2013), but the quality and ratio of components of the maternal diet also affects both fetal and postnatal development (Herring *et al.* 2018). Importantly, lipids play a role in fetal development and variations to dietary fat composition has major implications, both short- and long-term, on offspring health (Herrera 2002, Berti *et al.* 2016). For example, oleic acid, a monounsaturated fatty acid (MUFA) given in pregnancy to diabetic rats lowers phospholipids, cholesterol and free fatty acid content in foetuses (Capobianco *et al.* 2008a). Furthermore, in humans, the addition of olive oil to the diet in individuals with type 2 diabetes has beneficial effects on blood glucose and reducing insulin resistance (Ryan 2000).

Previous research from our group has indicated that an enriched olive-oil diet given during gestation to mothers with mild diabetes improves fetal and placental development (Capobianco *et al.* 2008a; Martinez *et al.* 2012, Kurtz *et al.* 2014a), mainly by reducing the intrauterine inflammatory environment and regulating lipid metabolic pathways such as fatty acid uptake, lipid synthesis and catabolism (Jawerbaum & Capobianco 2011). Furthermore, these beneficial effects were identified to be mediated, in part, by the activation of the entire nuclear peroxisome proliferator-receptor (PPAR) family, namely PPAR $\alpha$ , PPAR  $\beta/\delta$  and/or PPAR $\gamma$ . The three members of this family of nuclear receptors are involved in feto-placental development, cell proliferation, differentiation, and metabolism (carbohydrate, lipid, protein) (Rees *et al.* 2008). Nevertheless, PPARs represent critical sensors of environmental dietary stimuli and are crucial in the regulation of metabolism. As primary regulators of lipid metabolism at the cellular level, they help maintain metabolic homeostasis when energy or lipid dietary composition is altered (Bordoni *et al.* 2006).

In maternal diabetes, PPARs levels and transcriptional activity are impaired in the placenta and different fetal organs, with further influence on the postnatal stage (i.e. the fetal origins of metabolic diseases) (Rees *et al.* 2008, Jawerbaum & Capobianco 2011, Jawerbaum & White 2017). PPARs function as critical transcription factors when activated by unsaturated fatty acids, which are efficiently transported through the placenta to the uterus

(Herrera 2002, Bordoni *et al.* 2006). Furthermore, dietary supplements enriched in 6% olive oil or safflower oil during diabetic pregnancies have been shown to activate PPARs, leading to the prevention of the metabolic and pro-inflammatory impairments in the fetus with evident results in the offspring, including the increase in insulin secretion (Capobianco *et al.* 2008a, 2015, Higa *et al.* 2010).

While PPARs are ubiquitous in the pancreas during normal embryonic development (Braissant & Wahli 1998) and play an important role in pancreatic glucose and lipid metabolism, the role of *in utero* pancreatic PPAR activation remains elusive.

A previous report has indicated that oleic acid (the major component of olive oil), a natural activating ligand of PPARs, exhibits anti-diabetic and anti-inflammatory properties in the INS-1E pancreatic cell line (Ravnskjaer *et al.* 2010). A rat model of maternal mild diabetes is useful to study the programming of the pancreatic development and the putative beneficial effects of the intervention with a normolipidemic diet enriched in oleic acid. Therefore, we hypothesize that olive-oil supplementation during pregnancy to a mild pre-gestational diabetic rat will activate PPARs *in utero* and might benefit the pancreas of the offspring postnatally.

## Materials and methods

### Animals

The *in vivo* experiments followed the Principles of Laboratory Animals Care (NIH publication number 85-23, <https://olaw.nih.gov/policies-laws/phs-policy.htm>) and were approved by the Institutional Committee for the Care and Use of Experimental Animals (CICUAL, Resolution CD N° 3170/2015; School of Medicine, UBA, Argentina). Eight male and sixteen female adult Albino Wistar rats were purchased from the certified animal facilities of the School of Exact and Natural Sciences, University of Buenos Aires (UBA, Argentina). The rats were housed in the animal facilities of the Center for Pharmacological and Botanical Studies (CEFYO-UBA-CONICET, Argentina) on a 12 h light:12 h darkness cycle with humidity maintained at a 45–60% and temperature between  $21 \pm 2^\circ\text{C}$ . The rats had *ad libitum* access to food and water throughout the study. For mating the female rats, two females were placed in one cage with a male and mating was confirmed by the presence of spermatozoa in the vaginal smear the following morning. Two days after birth, female neonates from each rat were randomly selected to rendered diabetic by a s.c. injection of streptozotocin (90 mg/kg,

Sigma-Aldrich) diluted in citrate buffer (0.05 M, pH 4.5, Sigma-Aldrich), as described before (Kurtz *et al.* 2010), or received citrate buffer alone (controls). The health of the rats and the environmental parameters were checked and recorded daily. At 2 months of age, prior to mating to control males, female offspring were confirmed diabetic by a fasting glucose reading (higher than 130 mg/dL) with a hand-held glucometer (Accu-Check, Roche Diagnostics) without anesthesia from lancing the tail vein. Twenty-four female rats (8 control and 16 diabetic rats) were housed in separate cages (two female: one male rat ratio) and pregnancy was confirmed by the presence of spermatozoa in vaginal smears the next morning. No adverse effects were observed by the dietary interventions or procedures detailed subsequently. At day 1 of pregnancy, rats were allocated into three groups ( $n=8$  each). The number of rats used was determined by statistical power analysis. Eight control (C) and eight diabetic (D, randomly selected) rats received a normal commercial chow diet composed of (g/100 g): carbohydrates (50); proteins (25); fat (5), major fatty acids 16:0 (0.58), 18:0 (0.16), 18:1 (1.27), 18:2 (1.99), 18:3 (0.73); calories: 325 kcal/100 g (Asociacion Cooperativa Argentina, Buenos Aires, Argentina). A third group of eight diabetic rats randomly selected were supplemented with 6% olive oil (a supplement diet that is 354% enriched in oleic acid, PPAR activator) (D+OO) in the pellet. The composition of the diet was described previously (Capobianco *et al.* 2015) and contains: (1) normal standard diet (composition listed previously) and (2) olive-oil-supplemented diet (g/100 g): carbohydrates (48); proteins (24); fat (11), major fatty acids 16:0 (1.55), 18:0 (0.26), 18:1 (5.77), 18:2 (2.41), 18:3 (0.57); calories: 340 kcal/100g. Food and water were provided *ad libitum*. Food intake was similarly increased in the diabetic group that received or not the olive-oil dietary treatment: control:  $67 \pm 3$  g/kg/day, maternal diabetes:  $75 \pm 3$  g/kg/day, maternal diabetes+olive oil:  $73 \pm 3$  g/kg/day. Weight gain was similar in the evaluated groups (control:  $132 \pm 8$  g, maternal diabetes:  $135 \pm 9$  g, maternal diabetes+olive oil:  $119 \pm 10$  g). Fasting glycemia values, evaluated on day 20 of pregnancy, were similar in the diabetic group that received or not the olive-oil dietary treatment (control:  $101 \pm 10$  mg/dL, maternal diabetes:  $229 \pm 19$  mg/dL, maternal diabetes+olive oil:  $208 \pm 10$  mg/dL). After birth, all the rats were fed with a normal chow diet. Body weight and food intake were measured bi-weekly. Maternal body weight was similar at weaning in the evaluated groups (control:  $315 \pm 14$  g, maternal diabetes:  $318 \pm 12$  g, maternal diabetes+olive oil:  $324 \pm 15$  g). Offspring weight was evaluated on a per litter basis.

Each litter was weighted on day 2 of pregnancy and litter was adjusted to three males and three females. Housing conditions were maintained as described previously. At postnatal day 2 and at 5 months old, two female and two male rats per litter were killed by decapitation at 12:00 h. Pancreata were dissected immediately and fixed in 4% formalin or immersed in RNAlater (RNA later, Invitrogen). Glycemia was also measured before killing by a hand-held glucometer (Accu-Check, Roche Diagnostics) on postnatal day 2 and after 6 h fasting at 5 months old rats from blood obtained by lancing the tail vein.

### Immunofluorescence

After a 24-h fixation in 4% buffered formalin (west-Chester, PA, USA) pancreata were dehydrated and embedded in paraffin (University Hospital, Pathology Lab, London, ON, Canada) and sectioned in 5- $\mu$ m sections and mounted in Superfrost-Plus slides (Fischer Scientific). In order to localize  $\alpha$ -cells and  $\beta$ -cells within the islets of Langerhans, dual immunofluorescence was performed. Three 5- $\mu$ m sections, separated by at least 50  $\mu$ m, were deparaffinized in xylene, rehydrated in descending ethanol series (100%, 90%, 70%) and washed in tap water. Tissues were then blocked with 1–2 drops of Sniper (Biocare Medical, Concord, CA, USA) for 5 min. All antisera were diluted in antibody diluent solution (DakoCytomation). Tissues were then incubated overnight at 4°C in a humidified chamber with 1:50 guinea pig anti-insulin (Abcam) and 1:750 rabbit anti-glucagon (Novus Biologicals, Centennial, CO, USA) primary antibodies. Slides were then rinsed and incubated for 60 min in darkness in a humidified chamber with its correspondent secondary antibodies (Invitrogen) 1:500 Donkey anti-guinea pig (Alexa Flour 555), and 1:500 Donkey anti-rabbit (Alexa 488) fluorescent secondary antibodies and DAPI (Sigma-Aldrich) was used to counterstain nuclei. Coverslip was applied with the addition of an anti-fade mounting solution (Life Technologies). To establish the specificity of all antibodies, controls included substitution of the primary antibody with non-immune serum or omission of the secondary antibody.

To further identify the co-localization of  $\beta$ -cells with the different PPAR isotypes ( $\alpha$ ,  $\beta/\delta$  and  $\gamma$ ) within the islets of Langerhans, dual immunofluorescence was performed. After deparaffinization as described previously, tissues were treated with citrate buffer pH 6 in a decloaking chamber for 20 min for antigen retrieval. Slides were left to cool at room temperature, washed in PBS and blocked with 1–2 drops of Sniper (Biocare Medical) for 10 min at room temperature.

All antisera were diluted in antibody diluent solution (DakoCytomation). Primary antibodies anti-mouse insulin (1:200) (Sigma-Aldrich) with anti-rabbit PPAR $\alpha$  (1:100) (Abcam) or anti-rabbit PPAR $\beta/\delta$  (1:50) (Santa Cruz Biotechnology) and anti-rabbit PPAR $\gamma$  (1:50) (Santa Cruz Biotechnology) were incubated in a humidified chamber for 48 h at 4°C. Slides were then rinsed and incubated for 60 min in darkness in a humidified chamber with its correspondent secondary antibodies (Invitrogen) at a concentration of (1:500) Donkey anti-mouse (AlexaFluor 555) and (1:500) Donkey anti-rabbit (Alexafluor 488) at room temperature. This was followed by two 5-min PBS washes. Nuclear counterstain DAPI (Sigma-Aldrich, 1:500) was applied before the addition of coverslip with anti-fade mounting solution (Life Technologies). To establish the specificity of all antibodies, controls included substitution of the primary antibody with non-immune serum or omission of the secondary antibody.

### Morphometric analysis

Analysis of pancreatic sections was performed using a Carl Zeiss Axioskop transmitted light and fluorescent microscope (Carl Zeiss) with QImaging Micro Publisher 3.3 Real Time viewing camera (QImaging, Burnaby, BC, Canada). Digital images were captured with 40 $\times$  or 2.5 $\times$  objectives lens. Image analysis of sections and quantification of areas of interest was performed using ImageJ v1.51s software (NIH) (Chamson-Reig *et al.* 2009). Data processing and statistical analysis were performed using Excel v16.12 (Microsoft) and GraphPad Prism v7.00 (GraphPad Software).

For each analysis, five male and five female animals per group (one male and one female per litter, a total of 30 rats) were randomly selected. Subsequently, three random sections (separated for at least 50  $\mu$ m) from each pancreas were analyzed. Multiple fields of view were assessed upon the entire pancreas, to ensure all islets were analyzed. For each section, the following measurements were determined: total pancreatic area, islet area and total area occupied by  $\alpha$  and  $\beta$ -cells and  $\beta$ -cell mass in mg (total  $\beta$  cell area  $\times$  pancreatic weight/total pancreatic area). Islets were separated by size, clusters (<500  $\mu$ m<sup>2</sup>), small (500–5000  $\mu$ m<sup>2</sup>), medium (5000–10,000  $\mu$ m<sup>2</sup>) and large (>10,000  $\mu$ m<sup>2</sup>).

### RNA extraction and qPCR

At 5 months of age, eight female and eight male pancreata (one male and one female per litter) per

group of treatment (a total of 48 rats) were dissected and immersed immediately in RNAlater (Ambion) and stored at –80°C until RNA extraction. Total RNA was extracted using Qiagen RNeasy Plus kit (Qiagen) according to the manufacturer's specifications and stored until further analysis. Sample yield and purity was quantified by absorbance at 260 and 280 nm (value 1.7–2) using NanoDrop 2000c Spectrophotometer (Thermo Fisher Scientific). Transcript abundance for Ppar $\alpha$ ,  $\beta/\delta$ ,  $\gamma$ , insulin and Pdx-1 was analyzed using quantitative RT PCR (RT-qPCR). RNA was amplified using designed primers (Primer-BLAST A, NCBI, NIH) with a Power SYBR® Green RNA-to-CT™ 1-Step Kit (Applied Biosystems, Thermo Fisher Scientific) following manufacturer's protocol. Primer sequences are in Table 1. Relative quantification was performed using 2<sup>– $\Delta\Delta$  Ct</sup> method with  $\beta$ -actin as the housekeeping gene. Data was determined as the relative expression ratio to control samples.

### Cell culture

To further understand the direct effects of oleic acid on the expression profile of Ppars in the endocrine pancreas, two different cell lines were utilized as they represent specific endocrine cells. INS-1E cells is a  $\beta$ -cell line (insulin) and  $\alpha$ TC1–6 is an  $\alpha$ -cell line (glucagon). INS-1E cells were cultured in RPMI1640 supplemented with 11 mM glucose, 1 mM pyruvate, 10 mM HEPES, 100  $\mu$ M  $\beta$ -mercaptoethanol, 10% FBS and penicillin/streptomycin.  $\alpha$ TC1–6 cells were cultured in DMEM (Thermo Fisher Scientific) supplemented with 5.5 mM glucose, 2.5% FBS and 15% horse serum. For each cell line, 10<sup>5</sup> cells per well were cultured in 6-well plates for 24 h. Media were replaced with serum free media and cells were treated in the presence or absence of 5  $\mu$ M oleic acid (OA) (major component of olive oil) (Sigma-Aldrich) (Vassiliou *et al.* 2009), 1  $\mu$ M 15 deoxy $\Delta^{12,14}$ prostaglandin J2 (15dPGJ2)

**Table 1** Primer sequences for q-PCR.

PPAR $\alpha$	Forward	TCCTCTGGTTGTCCTTGA
PPAR $\alpha$	Reverse	TGTCAGTTCACAGGGAAGGC
PPAR $\beta/\delta$	Forward	GCTCCTGCTCACTGACAGAT
PPAR $\beta/\delta$	Reverse	CGTGGCCACTTCTCTTTCT
PPAR $\gamma$	Forward	CCTGTTGACCCAGAGCATGG
PPAR $\gamma$	Reverse	GGTCCACAGAGCTGATTCCG
Pdx-1	Forward	CCGCGTTCATCTCCCTTTC
Pdx-1	Reverse	TGCCCACTGGCTTTTCCA
Insulin	Forward	CCGGCAGAAGCGTGGCATT
Insulin	Reverse	CATTGCAGAGGGGTGGGCGG
$\beta$ -Actin	Forward	CGCGAGTACAACCTTCTTGC
$\beta$ -Actin	Reverse	ATACCCACCATCACACCCTG



(Cayman) (Capobianco *et al.* 2008a), 0.1  $\mu$ M Leukotriene B4 (LTB4) (Cayman) (Martínez *et al.* 2011) and 1  $\mu$ M Carbaprostacyclin (CPC) (Cayman) (Higa *et al.* 2007) for 24 h. At the end of incubation, total RNA was isolated using Qiagen total RNA isolation kit (RNeasy mini kit) according to the supplier's protocol. cDNA synthesis and real-time PCR were performed using Power SYBR® Green RNA-to-CT™ 1-Step Kit (Thermo Fisher Scientific). Primers specific for Ppar $\alpha$ , Ppar $\beta/\delta$  and Ppar $\gamma$ , Pdx-1 and insulin were used (Table 1). Relative expression levels were determined using 2<sup>- $\Delta\Delta$  Ct</sup> method.

### Statistical analysis

Data were presented as mean  $\pm$  s.e.m. One-way ANOVA followed by Bonferroni post-hoc test was used to compare all groups. In case of comparison of only two groups, we used *t*-test. The differences were considered statistically significant at *P* < 0.05. Statistical analysis was performed using Graph Pad Prism Version 7 (GraphPad).

## Results

### Body weight, pancreas weight and fasting glycemia

To understand the general effects of postnatal diabetes and the dietary supplementation with 6% olive oil on maternal outcomes, we measured body weight, pancreas weight and glycemia at day 2 and 5 months in male and female offspring. At day 2, there were no statistical differences between body and pancreas weight and/or glycemia within all treatment groups in both sexes (Table 2). By 5 months of age, male and female offspring exhibited no changes in body weight and pancreas weight within all the groups. However, glycemia, was significantly increased in the male and female offspring from the diabetic dam groups, compared to the controls (*P* < 0.05) (Table 3). Interestingly, the gestational dietary treatment with olive oil in diabetic mothers prevented the increased glycemia in the 5-month male offspring but not the female offspring (*P* < 0.05 vs control group) (Table 3).

### Pancreatic morphometry

To examine if alterations in pancreatic development underlie the changes in postnatal glycemia observed, the percentage of islet area was measured to determine the effects of the olive-oil supplementation on the postnatal

**Table 2** Weight and glycemia in 2-day-old female and male offspring.

	Control	Maternal diabetes	Maternal diabetes + olive oil
Females			
Body weight (g)	6.32 $\pm$ 0.14	6.32 $\pm$ 0.15	6.60 $\pm$ 0.12
Pancreas weight (g)	0.025 $\pm$ 0.003	0.027 $\pm$ 0.001	0.024 $\pm$ 0.001
Glycemia (mg/dL)	64 $\pm$ 2	69 $\pm$ 5	70 $\pm$ 3
Males			
Body weight (g)	6.42 $\pm$ 0.20	6.60 $\pm$ 0.16	6.20 $\pm$ 0.11
Pancreas weight (g)	0.022 $\pm$ 0.002	0.028 $\pm$ 0.001	0.031 $\pm$ 0.001
Glycemia (mg/dL)	61 $\pm$ 3	65 $\pm$ 4	69 $\pm$ 5

All values were expressed as mean  $\pm$  s.e.m. (*n* = 6–8 per litter/group). Body weight was evaluated on a per litter basis. Pancreas weight and glycemia were evaluated on two females and two males per litter. Significant differences between treatment groups determined by one-way ANOVA (*P* < 0.05).

endocrine pancreas in male and female offspring born to diabetic mothers.

At postnatal day 2, the percentage of islet area was statistically different in males between control and diabetic rats receiving olive oil and diabetic rats given vehicle (*P* < 0.05) (Fig. 1A). This was not seen in females (Fig. 1C). However, at 5 months of age, the percentage of

**Table 3** Weight and glycemia in 5-month old female and male offspring.

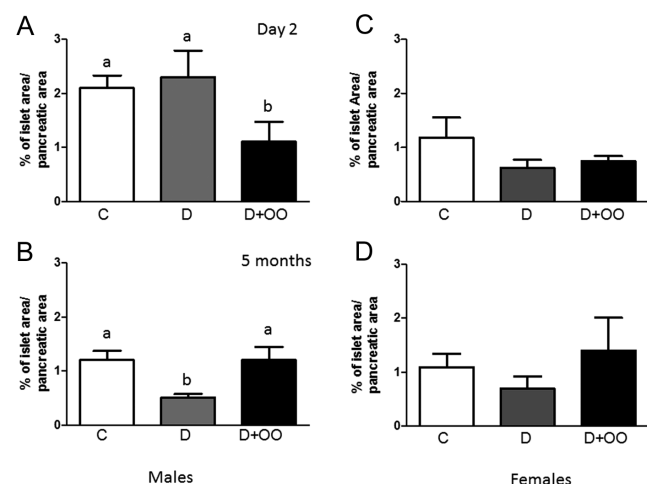
	Control	Maternal diabetes	Maternal diabetes + olive oil
Females			
Body weight (g)	383 $\pm$ 15	421 $\pm$ 11	380 $\pm$ 17
Pancreas weight (g)	1.03 $\pm$ 0.10	0.88 $\pm$ 0.062	0.83 $\pm$ 0.07
Glycemia (mg/dL)	104 $\pm$ 6 <sup>a</sup>	133 $\pm$ 6 <sup>b</sup>	140 $\pm$ 9 <sup>b</sup>
Males			
Body weight (g)	460 $\pm$ 18	499 $\pm$ 5	512 $\pm$ 17
Pancreas weight (g)	0.99 $\pm$ 0.09	0.97 $\pm$ 0.06	0.92 $\pm$ 0.02
Glycemia (mg/dL)	102 $\pm$ 12 <sup>a</sup>	147 $\pm$ 11 <sup>b</sup>	120 $\pm$ 12 <sup>ab</sup>

All values were expressed as mean  $\pm$  s.e.m. (*n* = 6–8 litters/group). Body weight was determined on a per adjusted-litter basis. Pancreas weight and glycemia were evaluated in two females and two males per litter. Significant differences between treatment groups determined by one-way ANOVA. Different letters represent means that are significantly different from one another according to Bonferroni post-hoc test (*P* < 0.05).

islet area was significantly reduced ( $P < 0.05$ ) in the male offspring from diabetic rats compared to the control group and significantly increased to control values ( $P < 0.05$ ) in the male offspring of diabetic mothers that received the olive-oil-supplemented diet (Fig. 1B). No differences between groups were seen in the females at the same age (Fig. 1C and D).

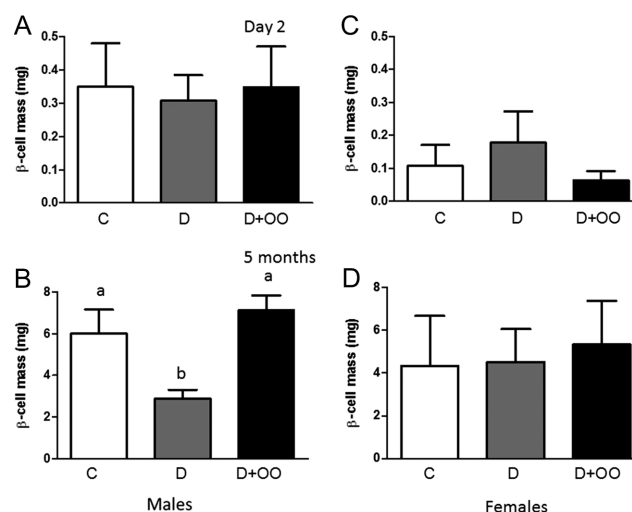
In addition, there was a significant decrease of the  $\beta$ -cell mass in the male offspring from diabetic rats ( $P < 0.01$ ) that was prevented by the dietary maternal treatment with olive oil (Fig. 2B). Females at either age did not exhibit any differences in  $\beta$ -cell mass between experimental treatments (Fig. 2C and D). In view of these results and given females did not demonstrate any differences in the islet architecture in postnatal life, we decided to focus further analysis only in males.

Islet number and size distribution in male offspring at 5 months of age was examined and the number of small ( $5000\text{--}10,000\text{ }\mu\text{m}^2$ ) and large ( $>10,000\text{ }\mu\text{m}^2$ ) islets of diabetic rats supplemented with olive oil was significantly increased ( $P < 0.05$ ) compared to either control or diabetic rats fed the standard chow diet (Fig. 3). Total number of islets was also increased in the adult offspring of diabetic rats fed with the diet supplemented with olive oil compared to the diabetic group that did not receive the olive oil ( $P < 0.001$ ) (Fig. 3). At this age, there was a



**Figure 1**

Representation of the percentage of islets in total pancreas area in offspring at day 2 and 5 months of age: graphs A (males) and C (females) represents day 2 and graphs B (males) and D (females) 5 months of age. Bars represent control animals (white), diabetic animals (grey) and diabetic treated with olive oil (black). All values were expressed as mean  $\pm$  S.E.M. ( $n = 6\text{--}8$  animals/group). Significant differences between treatment groups were determined by one-way ANOVA. Different letters represent means that are significantly different from one another according to Bonferroni post-hoc test ( $P < 0.05$ ).



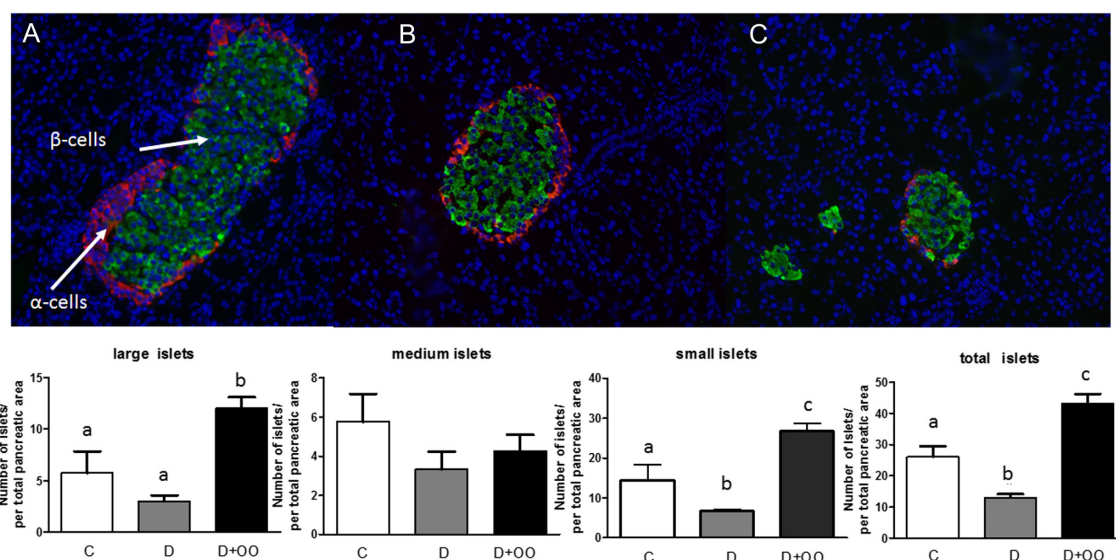
**Figure 2**

Representation of the total  $\beta$ -cell mass in offspring pancreata at day 2 and 5 months of age: graphs A (males) and C (females) day 2 and graphs B (males) and D (females) 5 months of age. Bars represent control animals (white), diabetic animals (grey) and diabetic treated with olive oil (black). All values were expressed as mean  $\pm$  S.E.M. ( $n = 6\text{--}8$  animals/group). Significant differences between treatment groups were determined by one-way ANOVA. Different letters represent means that are significantly different from one another according to Bonferroni post-hoc test ( $P < 0.05$ ).

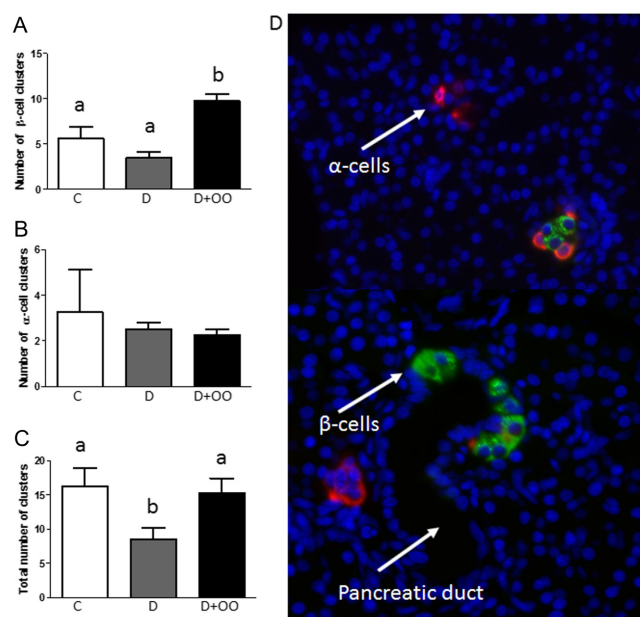
significant increase in islets clusters (2–3 cells) budding near pancreatic ducts (most of them  $\beta$ -cell origin) (Fig. 4A) of diabetic rats fed the olive-oil-supplemented diet compared to the diabetic group ( $P < 0.01$ ). However, no changes in  $\alpha$ -cell clusters were observed between the groups (Fig. 4B). Collectively, this resulted in an increase in the total number of clusters in the pancreas of olive-oil-supplemented diabetic rat offspring compared to diabetic rats alone (Fig. 4C).

### Effects of maternal olive-oil supplementation on pancreatic PPAR expression and their distribution within the endocrine pancreas in the offspring

Real-time quantitative PCR was employed to assess the effects of olive-oil supplementation during pregnancy on postnatal pancreatic PPAR gene expression. No differential expression on the steady-state levels of PPAR $\alpha$  was seen at 5 months of age (Fig. 6A). By immunofluorescence, PPAR $\alpha$  was localized to the mantle of the islet ( $\alpha$  cell area) suggesting co-localization with glucagon secreting cells (Fig. 5A). However, pancreatic PPAR $\beta/\delta$  expression was significantly reduced ( $P < 0.01$ ) in the adult offspring of diabetic rats compared to controls but was restored in the offspring of diabetic rats that received olive oil as a supplement during pregnancy (Fig. 6B). By immunofluorescence,

**Figure 3**

Representative microphotographs of large (A), medium (B) and small islets (C). Arrows indicate  $\beta$  cells (red) and  $\alpha$  cells (brown). Column graphs represent the distribution of islets by size within the different treatments from male 5-month-old rats. Bars represent control animals (white), diabetic animals (grey) and diabetic treated with olive oil (black). All values were expressed as mean  $\pm$  S.E.M. ( $n = 6-8$  animals/group). Significant differences between treatment groups were determined by one-way ANOVA. Different letters represent means that are significantly different from one another according to Bonferroni post-hoc test ( $P < 0.05$ ).

**Figure 4**

Representative microphotograph of beta cell clusters near ducts. The arrows identify insulin secreting  $\beta$  cells. On the left-hand side, graphs represent the number of (A)  $\beta$ , (B)  $\alpha$  and (C) total clusters per total pancreas area in male offspring at 5 months of age. Bars represent control animals (white), diabetic animals (grey) and diabetic treated with olive oil (black). All values were expressed as mean  $\pm$  S.E.M. ( $n = 6-8$  animals/group). Significant differences between treatment groups were determined by one-way ANOVA. Different letters represent means that are significantly different from one another according to Bonferroni post-hoc test ( $P < 0.05$ ).

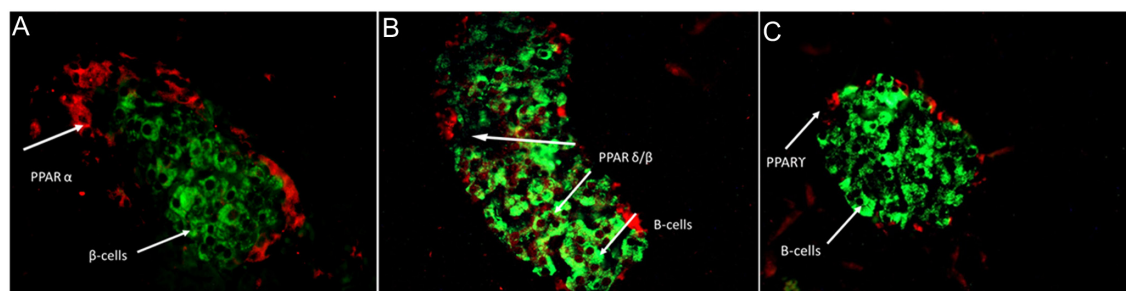
PPAR $\beta/\delta$  was also localized at the mantle of the islet (to the cytoplasm of  $\alpha$  cells) and the nuclei of  $\beta$ -cells (Fig. 5B) suggesting some role in  $\beta$ -cell differentiation or function. Finally, PPAR $\gamma$  was significantly reduced ( $P < 0.05$ ) in the pancreas of the offspring of diabetic rats regardless of olive-oil supplementation (Fig. 6C). Moreover, PPAR $\gamma$  was also localized in the area where  $\alpha$  cells are present in the rat islets by dual immunofluorescence (Fig. 5C).

#### Examining the direct effects of oleic acid on pancreatic PPAR expression

When both cell lines were treated with oleic acid for 24 h, INS-1E cells showed a differential profile of PPAR gene expression compared to  $\alpha$ TC1-6 cells. Treatment with OA reduced gene expression of PPAR $\alpha$  (~20%) and PPAR $\gamma$  (~96%) and increased gene expression of PPAR $\beta/\delta$  (~20%) compared to corresponding controls in INS-1E cells. Meanwhile in  $\alpha$ TC1-6, OA increased the gene expression of PPAR $\alpha$ , PPAR $\beta/\delta$  and PPAR $\gamma$  mRNA around ~310%, ~260%, and ~410 %, respectively, compared to controls. These results show for the first time that PPAR expression can be induced also in  $\alpha$ -cells. Mainly, in this case, oleic acid significantly increased the gene expression of PPAR $\alpha$  ( $P < 0.01$ ), PPAR $\beta/\delta$  ( $P < 0.05$ ) and PPAR $\gamma$  ( $P < 0.01$ ) in  $\alpha$ TC1-6 cells compared to INS-1E cells (Fig. 7A).

In order to confirm if these differences seen in INS-1E cells and  $\alpha$ TC1-6 cells occur in the presence of other PPAR



**Figure 5**

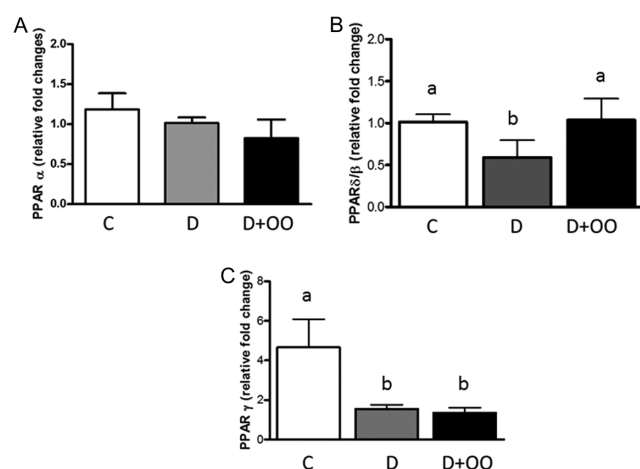
Representative microphotographs of PPAR $\alpha$ , PPAR $\beta/\delta$  and  $\gamma$ . (A) Arrows identify PPAR $\alpha$  (red) and insulin (green). (B) Arrows identify PPAR $\beta/\delta$  (red) in the nucleus of  $\beta$ -cells and insulin (green). (C) Arrows identify PPAR $\gamma$  (red) and insulin (green).

natural agonists, we tested and compared LTB<sub>4</sub>, CPC and 15dPGJ<sub>2</sub>. LTB<sub>4</sub>, a PPAR $\alpha$  agonist, significantly increased mRNA expression of all PPARs in  $\alpha$  cells compared to  $\beta$  cells with different levels of significance (Fig. 7B) ( $P < 0.01$ ), ( $P < 0.05$ ), ( $P < 0.05$ ), respectively. Also, CPC, a PPAR $\beta/\delta$  agonist, did not have any effect on any of the PPARs in INS-1E cells. Although, in  $\alpha$ TC1-6 cells, CPC significantly increased the expression of PPAR $\alpha$  (~297%) and PPAR $\gamma$  (279%) (Fig. 7C). Moreover, 15dPGJ<sub>2</sub> (PPAR $\gamma$  agonist) increased the expression of PPAR $\gamma$  mRNA in INS-1E cells (~191%) with no effect on  $\alpha$ TC1-6. However, 15dPGJ<sub>2</sub> significantly increased PPAR $\beta/\delta$  gene expression (~127%) in  $\alpha$ TC1-6 cells (Fig. 7D). These results imply that PPARs can be induced in either  $\alpha$ - or  $\beta$ -cells and that their expression depends on the stimulus.

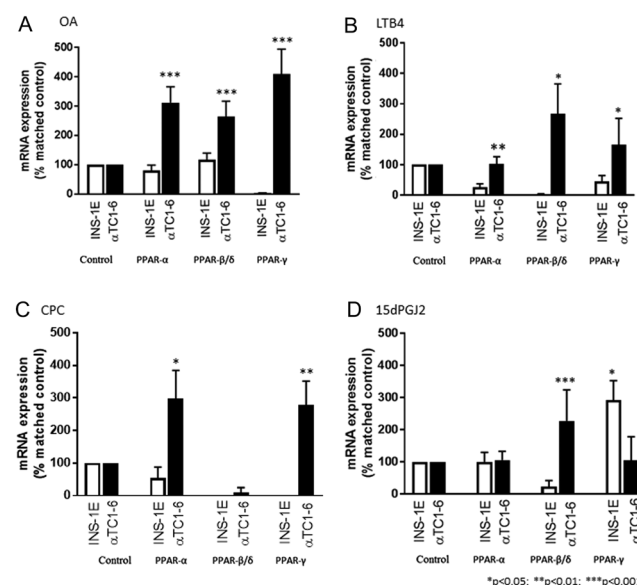
Interestingly, when the downstream PPAR target genes (e.g. Pdx-1 and insulin) were measured after OA, 15dPGJ<sub>2</sub> and LTB<sub>4</sub> treatments in INS-1E cells, both target genes were significantly increased, while treatment of the cells with CPC had no effect (Fig. 8).

## Discussion

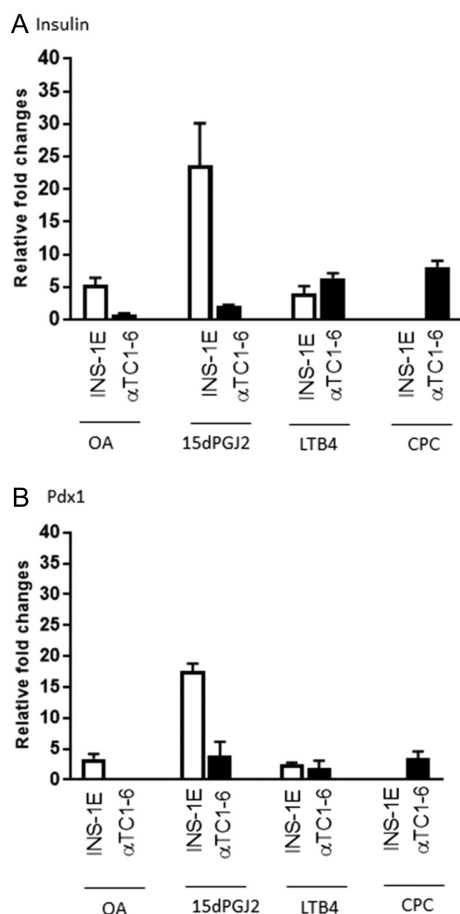
Population studies had shown that dietary habits resulting high in monounsaturated fatty acids (MUFAs) attributed

**Figure 6**

Expression of PPAR $\alpha$  (A), PPAR $\beta/\delta$  (B) and PPAR $\gamma$  (C) by q-PCR. Bars represent control animals (white), diabetic animals (grey) and diabetic treated with olive oil (black). \* $P < 0.05$  and \*\*\* $P < 0.001$ . All values were expressed as mean  $\pm$  s.e.m. ( $n = 6-8$  animals/group). Significant differences between treatment groups were determined by one-way ANOVA. Different letters represent means that are significantly different from one another according to Bonferroni post-hoc test ( $P < 0.05$ ).

**Figure 7**

INS-1E cells and  $\alpha$ TC1-6 cells treated with oleic acid (OA; 5  $\mu$ M), leukotriene B<sub>4</sub> (LTB<sub>4</sub>; 0.1  $\mu$ M), 15 deoxy prostaglandin J<sub>2</sub> (15dPGJ<sub>2</sub>; 1  $\mu$ M), and carbaprostacyclin (CPC; 1  $\mu$ M) for 24 h. Gene expression levels of PPAR $\alpha$ , PPAR $\beta/\delta$  and PPAR $\gamma$  were determined following treatment with (A) OA, (B) LTB<sub>4</sub> (C) 15dPGJ<sub>2</sub>, and (D) CPC using qRT-PCR. Levels of PPAR $\alpha$ , PPAR $\beta/\delta$  and PPAR $\gamma$  were normalized to an internal control,  $\beta$ -actin. The normalized levels of transcripts were shown as relative percent to that of non-treated control.  $t$ -test analysis ( $\alpha = 0.05$ ) was performed to compare the levels of difference between  $\alpha$ TC1-6 cells and INS-1E cells for each gene. \* $P < 0.05$ ; \*\* $P < 0.01$ ; \*\*\* $P < 0.001$ .

**Figure 8**

mRNA expression levels of (A) insulin and (B) Pdx-1 after treatment of INS-1E cells and  $\alpha$ TC1-6 cells with OA, PGJ2, LTB4 and CPC determined by qRT-PCR. Log2 fold changes were calculated compared to the respective controls.

to olive-oil consumption leads to overall reduced inflammatory markers and better health outcomes (Jiménez-Gómez *et al.* 2009, Schwingshackl & Hoffmann 2014). Moreover, oleic acid, the major component of olive oil, reduces LDL and total cholesterol levels with beneficial consequences on blood sugar control and reducing insulin resistance, culminating in a better management of type 2 diabetes (T2D). Oleic acid also reverses inflammation in obesity (Ryan 2000). Aside from regulating glycemia in adulthood, olive oil is promising during development as well (Jawerbaum & Capobianco 2011).

Previously, we have shown that daily dietary olive-oil supplementation administered to mildly diabetic rats during pregnancy improved the development of the placenta and fetus with beneficial effects in different organs, including the heart and the lung (Kurtz *et al.* 2014a,b, Capobianco *et al.* 2008a). The benefit to these organs has been attributed to PPARs activation and

restoration of PPAR levels (Capobianco *et al.* 2008b, 2015, Kurtz *et al.* 2014a). Specifically, these PPARs have anti-inflammatory functions and their expression is reduced in the placenta from diabetic rats and from pre-gestational and gestational diabetic patients (Capobianco *et al.* 2005, 2013, Martínez *et al.* 2008, 2011, Wieser *et al.* 2008, Arck *et al.* 2010, Holdsworth-Carson *et al.* 2010). Moreover, impaired PPAR pathways and levels of PPARs endogenous ligands in the placenta are rescued with olive-oil supplementation (Capobianco *et al.* 2008a). Besides, we previously found that maternal olive-oil supplementation increases insulin levels and decreases triglycerides in the 5-month-old offspring from diabetic rats (Capobianco *et al.* 2015). The proposed dietary supplementation provides half of the calories from lipids derived from olive oil, and thus, it would be feasible to be recommended in humans, as it corresponds to three daily spoons of olive oil. Therefore, we proposed that maternal dietary manipulations (such as the addition of olive oil) may add to the benefits of the tight insulin monitoring to mothers with pre-gestational or gestational diabetes on the development of the pancreata in postnatal life.

In rodents, the pancreas and other metabolic organs are not fully developed at birth. During e-18.5 to e-20.5,  $\beta$ -cells duplicate in number (Kaung 1994). Any alterations in this period are of importance as it determines the health or predisposition to develop disease of the individual long-term. By weaning, the quantity and quality of  $\beta$  cells are finally defined (Kaung 1994, Petrik *et al.* 1999, Zhang *et al.* 2005). Tight regulation of  $\beta$ -cell mass is required for preserving insulin secretion capacity over a life time.

In this study, by postnatal day 2, no significant differences were observed between treatments and sexes with respect to  $\beta$ -cell mass (mg), suggesting that at this time point the effects of maternal status of disease or diet had not manifested. However, by 5 months of age, males of diabetic mothers were overtly glucose intolerant (Capobianco *et al.* 2015) and exhibited reduced  $\beta$ -cell mass. Interestingly, maternal olive-oil supplementation prevented fasting hyperglycemia in the male offspring due, in part, to prevention of  $\beta$ -cell mass and total pancreatic islet loss. The benefits of olive-oil supplementation in these offspring could also be attributed to higher number of larger islets and clusters near the ducts (mainly  $\beta$ -cells). Nevertheless, the increased  $\beta$ -cell number observed does not always account for hyperinsulinemia and hypoglycaemia (Zhang *et al.* 2005) or changes in plasma insulin levels (Nguyen *et al.* 2006). Given females did not show any glycemic differences within treatments at either

developmental age, further studies were only conducted in males.

Previous studies have demonstrated that, during development, PPAR $\alpha$ ,  $\beta/\delta$  and  $\gamma$  are ubiquitously distributed in the pancreas and play essential roles in the regulation of its cellular differentiation, proliferation and metabolism (Braissant *et al.* 1996). During late gestation (i.e. gestational day 18.5), PPAR $\alpha$  is expressed in the pancreas during a period when cells adapt from high-fat oxidation to high-glucose oxidation (Gremlich *et al.* 2005). Deletion of PPAR $\alpha$  in *ob/ob* mice developed pancreatic  $\beta$ -cell dysfunction characterized by reduced mean islet area and decreased insulin secretion in response to glucose *in vitro* and *in vivo* (Lalloyer *et al.* 2006). Although PPAR isoforms are expressed in islets (Braissant *et al.* 1996), their function is still unclear.

In the adult rat pancreas, they are expressed in both the exocrine and the endocrine pancreas and by *in situ* hybridization and gene expression analysis PPAR $\alpha$  and have lower expression when compared with PPAR $\beta/\delta$  (Braissant *et al.* 1996). PPAR $\beta/\delta$  is highly expressed in  $\beta$ -cells (Iglesias *et al.* 2012). Furthermore, in the diabetic male offspring at 5 months of age, the expression of PPAR $\beta/\delta$  was reduced significantly but restored to control levels in the offspring of diabetic mothers treated with olive oil. In this group, PPAR $\beta/\delta$  was found in the nucleus of  $\beta$  cells suggesting that may be involved in  $\beta$ -cell differentiation and proliferation as observed histologically. Under normal cell culture conditions, we further determined that the steady-state levels of PPAR $\beta/\delta$  mRNA were increased in both INS-1E and  $\alpha$ TC1-6 cells. Activation of PPAR $\beta/\delta$  by its ligands increases fatty acid oxidation capacity in INS-1E cells, enhances glucose stimulated insulin secretion (GSIS) in islets and protects GSIS against the effects of prolonged fatty acid exposure (Cohen *et al.* 2011). In db/db mice, prolonged treatment with PPAR $\beta/\delta$  agonists (GW501516) reduced blood glucose by improving insulin sensitivity and islet function (Yang *et al.* 2016). A recent report indicates that a pharmacological ligand of PPAR $\beta/\delta$  amplifies the adaptive insulin secretory response of  $\beta$ -cells upon exposure to increasing concentrations of glucose in both INS-1E and rat isolated islets (Winzell *et al.* 2010). Others suggested that PPAR $\beta/\delta$  is a master regulator of functions associated with each step of insulin secretion (granule biosynthesis, vesicle trafficking and exocytosis) and may have a repressive role controlling  $\beta$ -cell mass and insulin exocytosis (Hellemans *et al.* 2007) with a protective effect against metabolic stress in  $\beta$ -cells (Ravnskjaer *et al.* 2010).

Taking into consideration all the observations listed previously, we suggest that PPAR $\beta/\delta$  may have had a role in

restoring the  $\beta$ -cell mass in the male offspring of diabetic rats that received the olive-oil supplementation during pregnancy. In contrast, PPAR $\alpha$  gene expression did not differ between treatment groups at 5 months of age, and it was only localized in the cytoplasm of  $\alpha$  cells, suggesting that it has minimal effects on  $\beta$ -cell gene expression in adulthood. Furthermore, PPAR $\alpha$  mRNA was also increased in  $\alpha$ TC1-6 cells after OA exposure. Finally, we examined the expression of PPAR $\gamma$  and our studies showed a reduced expression of PPAR $\gamma$  in the 5-month pancreas of the offspring of diabetic rats, which was not prevented by the maternal treatment with olive oil, and that this PPAR isotype was only localized in  $\alpha$  cells. While it has been shown that PPAR $\gamma$  is localized in both  $\beta$  cells (Braissant *et al.* 1996) and in  $\alpha$  cells (Laybutt *et al.* 2002, Gupta *et al.* 2008), we were only able to detect its localization in  $\alpha$  cells. This PPAR isotype has been previously demonstrated to represses glucagon transcription in the islets (Rosen *et al.* 2003) and its signaling is implicated in the regulation of  $\beta$ -cell proliferation in adults. Mice with deleted expression of PPAR $\gamma$  in  $\beta$ -cell had significant islet hyperplasia but, despite this alteration in  $\beta$ -cell mass, no effect on glucose homeostasis was noted (Rosen *et al.* 2003, Moibi *et al.* 2007). Another study showed that PPAR $\gamma$  may regulate Pdx-1 transcription (Kim *et al.* 2002, Gupta *et al.* 2008), glucokinase (Kim *et al.* 2000), glucose transporter (Glut2) (Gupta *et al.* 2008) and indirectly  $\beta$ -cell function and mass (Laybutt *et al.* 2002). In our hands, the *in vitro* experiments showed that exposure with OA increased PPAR $\gamma$  mRNA only in  $\alpha$ TC1-6 cells where it could be acting as a repressor.

In order to elucidate if the *in vitro* effects of OA was specific, we tested both cell lines with three different natural PPAR agonists and found that they were differentially expressed in both cell lines. To this end, the expression of PPARs did not show a common characteristic among all three isotypes of PPARs in  $\beta$  cells. However, aside of OA, all administered agonists dramatically reduced PPAR $\beta/\delta$  expression in  $\beta$ -cells. Although, PPARs downstream target genes such as PDX-1 and insulin were significantly increased in (INS-1E cells) after OA, 15dPGJ2 and LTB4 treatments.

Another important point to address from these results is the novelty that both OA and LTB4 increased the expression levels for all three isotypes of PPARs in  $\alpha$ TC1-6 cells. However, such pattern was not shown in INS-1E cells, suggesting that OA has a differential effect in  $\alpha$  cell compared to  $\beta$  cell *in vitro*.

In summary, this study has identified the distribution and the expression of PPARs in different cell populations

within the endocrine pancreas when maternally exposed to a diet enriched in oleic acid. We also demonstrated histologically that PPAR $\beta/\delta$  is present in the  $\beta$  cells at 5 months postnatal, while PPAR $\alpha$  and  $\gamma$  are only in  $\alpha$  cells suggesting a different role of these PPARs in the adult endocrine pancreas. To further elucidate the underlying molecular mechanisms involved, we also examined the direct effects of oleic acid in  $\alpha$ - and  $\beta$ -cell lines. We first found that all PPARs were differentially expressed in both cell lines. Interestingly, all PPAR isoforms were present in  $\alpha$ TC1–6 cells when stimulated by oleic acid. The up-regulated gene expression of all three PPARs in  $\alpha$ TC1–6 cells suggests a role for these nuclear receptors in a counter regulatory mechanism between  $\alpha$  and  $\beta$  cells which are likely important for the maintenance of  $\beta$ -cell survival and function. Furthermore, we showed for the first time to our knowledge *in vivo* and *in vitro* the presence of PPARs in  $\alpha$  cells. Collectively, based on these observations, we suggest that, in male offspring of mildly diabetic mothers, the early exposure of 6% olive oil may have permitted a normal pancreas development, likely due to the indirect effect of the maternal diet (e.g. oleic acid) on the intrauterine micro-environment (Capobianco *et al.* 2008a) or by a direct effect by the activation of PPARs during fetal pancreatic development. Both interactions may have programmed  $\beta$  cells *in utero* and rescued male offspring from an early onset of T2D in adulthood.

#### Declaration of interest

There is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

#### Acknowledgements and Funding

The authors gratefully acknowledge Dr Savita Dhavantari for editing the manuscript and for the financial support the Agencia Nacional de Promocion Cientifica y Tecnologica de Argentina (PICT 2015-0130 and PICT 2017-0126) and the IRF 2015-2018 grant from the Lawson Research Institute, London, Ontario, Canada.

#### Author contributions

AJ and EA designed the study, while BT, EV and FA performed all experiments and data analysis. DBH assisted with real-time PCR experiments and data analysis. EA, AJ, and DBH assisted in preparation and revisions of the manuscript.

## References

Arck P, Toth B, Pestka A & Jeschke U 2010 Nuclear receptors of the peroxisome proliferator-activated receptor (PPAR) family in gestational diabetes: from animal models to clinical trials.

*Biology of Reproduction* **83** 168–176. (<https://doi.org/10.1095/biolreprod.110.083550>)

Berti C, Cetin I, Agostoni C, Desoye G, Devlieger R, Emmett PM, Ensenauer R, Hauner H, Herrera E, Hoesli I, *et al.* 2016 Pregnancy and infants' outcome: nutritional and metabolic implications. *Critical Reviews in Food Science and Nutrition* **56** 82–91. (<https://doi.org/10.1080/10408398.2012.745477>)

Bordon A, Di Nunzio M, Danesi F & Biagi PL 2006 Polyunsaturated fatty acids: from diet to binding to ppar and other nuclear receptors. *Genes & Nutrition* **1** 95–106. (<https://doi.org/10.1007/BF02829951>)

Braissant O & Wahli W 1998 Differential expression of peroxisome proliferator-activated receptor- $\alpha$ , - $\beta$ , and - $\gamma$  during rat embryonic development. *Endocrinology* **139** 2748–2754. (<https://doi.org/10.1210/endo.139.6.6049>)

Braissant O, Foulfelle F, Scotto C, Dauça M & Wahli W 1996 Differential expression of peroxisome proliferator-activated receptors (PPARs): tissue distribution of PPAR- $\alpha$ , - $\beta$ , and - $\gamma$  in the adult rat. *Endocrinology* **137** 354–366. (<https://doi.org/10.1210/endo.137.1.8536636>)

Capobianco E, Jawerbaum A, Romanini MC, White V, Pustovrh C, Higa R, Martinez N, Mugnaini MT, Soñez C & Gonzalez E 2005 15-deoxy- $\Delta$ 12,14-prostaglandin J2 and peroxisome proliferator-activated receptor  $\gamma$  (PPAR $\gamma$ ) levels in term placental tissues from control and diabetic rats: modulatory effects of a PPAR $\gamma$  agonist on nitridergic and lipid placental metabolism. *Reproduction, Fertility and Development* **17** 423–433. (<https://doi.org/10.1071/RD04067>)

Capobianco E, Martínez N, Higa R, White V & Jawerbaum A 2008a The effects of maternal dietary treatments with natural PPAR ligands on lipid metabolism in fetuses from control and diabetic rats. *Prostaglandins Leukotrienes and Essential Fatty Acids* **79** 191–199. (<https://doi.org/10.1016/j.plefa.2008.08.003>)

Capobianco E, White V, Higa R, Martínez N & Jawerbaum A 2008b Effects of natural ligands of PPAR $\gamma$  on lipid metabolism in placental tissues from healthy and diabetic rats. *Molecular Human Reproduction* **14** 491–499. (<https://doi.org/10.1093/molehr/gan039>)

Capobianco E, Martínez N, Fornes D, Higa R, Di Marco I, Basualdo M, Faingold M & Jawerbaum A 2013 PPAR activation as a regulator of lipid metabolism, nitric oxide production and lipid peroxidation in the placenta from type 2 diabetic patients. *Molecular and Cellular Endocrinology* **377** 7–15. (<https://doi.org/10.1016/j.mce.2013.06.027>)

Capobianco E, Pelesson M, Careaga V, Fornes D, Canosa I, Higa R, Maier M & Jawerbaum A 2015 Intrauterine programming of lipid metabolic alterations in the heart of the offspring of diabetic rats is prevented by maternal diets enriched in olive oil. *Molecular Nutrition and Food Research* **59** 1997–2007. (<https://doi.org/10.1002/mnfr.201500334>)

Catalano PM, Kirwan JP, Haugel-de Mouzon S & King J 2003 Gestational diabetes and insulin resistance: role in short- and long-term implications for mother and fetus. *Journal of Nutrition* **133** (Supplement 2) 1674S–1683S. (<https://doi.org/10.1093/jn/133.5.1674S>)

Chamson-Reig A, Arany EJ, Summers K & Hill DJ 2009 A low protein diet in early life delays the onset of diabetes in the non-obese diabetic mouse. *Journal of Endocrinology* **201** 231–239. (<https://doi.org/10.1677/JOE-09-0002>)

Chon S, Fetia L, Sobngwi E, Riveline J, Nguewa J, Baz B, Choukem S, Boudou P, Hadjadj S, Larger E, *et al.* 2014 Fetal exposure to maternal type 1 diabetes is associated with reduced insulin secretory function in adult offspring. *Diabetes* **63** A406–A407. (<https://doi.org/http://dx.doi.org/10.2337/db14-1317-1629>)

Cohen G, Riahi Y, Shamni O, Guichardant M, Chatgililoglu C, Ferreri C, Kaiser N & Sasson S 2011 Role of lipid peroxidation and PPAR- $\delta$  in amplifying glucose-stimulated insulin secretion. *Diabetes* **60** 2830–2842.



- Correa A, Gilboa S, Besser L, Botto L, Moore C, Hobbs C, Cleves M, Riehle-Colarusso T, Waller D & Reece E 2008 Diabetes mellitus and birth defects. *American Journal of Obstetrics and Gynecology* **199** 1–9. (<https://doi.org/10.1016/j.ajog.2008.08.034>)
- Gremlich S, Nolan C, Roduit R, Burcelin R, Peyot ML, Delghingaro-Augusto V, Desvergne B, Michalik L, Prentki M & Wahli W 2005 Pancreatic islet adaptation to fasting is dependent on peroxisome proliferator-activated receptor  $\alpha$  transcriptional up-regulation of fatty acid oxidation. *Endocrinology* **146** 375–382. (<https://doi.org/10.1210/en.2004-0667>)
- Gupta D, Jetton TL, Mortensen RM, Zhong Duan S, Peshavaria M & Leahy JL 2008 In vivo and in vitro studies of a functional peroxisome proliferator-activated receptor gamma response element in the mouse PDX-1 promoter. *Journal of Biological Chemistry* **283** 32462–32470. (<https://doi.org/10.1074/jbc.M801813200>)
- Harris BS, Bishop KC, Kemeny HR, Walker JS, Rhee E & Kuller JA 2017 Risk factors for birth defects. *Obstetrical and Gynecological Survey* **72** 123–135. (<https://doi.org/10.1097/OGX.0000000000000405>)
- Hellemans K, Kerckhofs K, Hannaert J-C, Martens G, Van Veldhoven P & Pipeleers D 2007 Peroxisome proliferator-activated receptor alpha-retinoid X receptor agonists induce beta-cell protection against palmitate toxicity. *FEBS Journal* **274** 6094–6105. (<https://doi.org/10.1111/j.1742-4658.2007.06131.x>)
- Herrera E 2002 Implications of dietary fatty acids during pregnancy on placental, fetal and postnatal development – a review. *Placenta* **23** Supplement A S9–19. (<https://doi.org/10.1053/plac.2002.0771>)
- Herring CM, Bazer FW, Johnson GA & Wu G 2018 Impacts of maternal dietary protein intake on fetal survival, growth, and development. *Experimental Biology and Medicine* **243** 525–533. (<https://doi.org/10.1177/1535370218758275>)
- Higa R, Gonzalez E, Pustovrk MC, White V, Capobianco E, Martinez N & Jawerbaum A 2007 PPAR delta and its activator PGI2 are reduced in diabetic embryopathy: involvement PPAR delta activation in lipid metabolic and signaling pathways in rat embryo early organogenesis. *Molecular Human Reproduction* **13** 103–110.
- Higa R, White V, Martínez N, Kurtz M, Capobianco E & Jawerbaum A 2010 Safflower and olive oil dietary treatments rescue aberrant embryonic arachidonic acid and nitric oxide metabolism and prevent diabetic embryopathy in rats. *Molecular Human Reproduction* **16** 286–295. (<https://doi.org/10.1093/molehr/gap109>)
- Holdsworth-Carson S, Lim R, Mitton A, Whitehead C, Rice GE, Permezel M & Lappas M 2010 Peroxisome proliferator-activated receptors are altered in pathologies of the human placenta: gestational diabetes mellitus, intrauterine growth restriction and preeclampsia. *Placenta* **31** 222–229. (<https://doi.org/10.1016/j.placenta.2009.12.009>)
- Iglesias J, Barg S, Vallois D, Lahiri S, Roger C, Yessoufou A, Pradevand S, McDonald A, Bonal C, Reimann F, *et al.* 2012 PPAR $\beta/\delta$  affects pancreatic  $\beta$  cell mass and insulin secretion in mice. *Journal of Clinical Investigation* **122** 4105–4117. (<https://doi.org/10.1172/JCI42127>)
- Jawerbaum A & Capobianco E 2011 Review: Effects of PPAR activation in the placenta and the fetus: implications in maternal diabetes. *Placenta* **32** (Supplement 2) S212–S217. (<https://doi.org/10.1016/j.placenta.2010.12.002>)
- Jawerbaum A & White V 2017 Review on intrauterine programming: consequences in rodent models of mild diabetes and mild fat overfeeding are not mild. *Placenta* **52** 21–32. (<https://doi.org/10.1016/j.placenta.2017.02.009>)
- Jiménez-Gómez Y, López-Miranda J, Blanco-Colio LM, Marín C, Pérez-Martínez P, Ruano J, Paniagua JA, Rodríguez F, Egido J & Pérez-Jiménez F 2009 Olive oil and walnut breakfasts reduce the postprandial inflammatory response in mononuclear cells compared with a butter breakfast in healthy men. *Atherosclerosis* **204** E70–E76. (<https://doi.org/10.1016/j.atherosclerosis.2008.09.011>)
- Kaung HL 1994 Growth dynamics of pancreatic islet cell populations during fetal and neonatal development of the rat. *Developmental Dynamics* **200** 163–175. (<https://doi.org/10.1002/aja.1002000208>)
- Kim HI, Kim JW, Kim SH, Cha JY, Kim KS & Ahn YH 2000 Identification and functional characterization of the peroxisomal proliferator response element in rat GLUT2 promoter. *Diabetes* **49** 1517–1524. (<https://doi.org/10.2337/diabetes.49.9.1517>)
- Kim HI, Cha JY, Kim SY, Kim JW, Roh KJ, Seong JK, Lee NT, Choi KY, Kim KS & Ahn YH 2002 Peroxisomal proliferator-activated receptor- $\gamma$  upregulates glucokinase gene expression in  $\beta$ -cells. *Diabetes* **51** 676–685. (<https://doi.org/10.2337/diabetes.51.3.676>)
- Kurtz M, Capobianco E, Martínez N, Fernández J, Higa R, White V & Jawerbaum A 2010 Carbaprostacyclin, a PPAR $\delta$  agonist, ameliorates excess lipid accumulation in diabetic rat placentas. *Life Sciences* **86** 781–790. (<https://doi.org/10.1016/j.lfs.2010.03.008>)
- Kurtz M, Capobianco E, Martinez N, Roberti SL, Arany E & Jawerbaum A 2014a PPAR ligands improve impaired metabolic pathways in fetal hearts of diabetic rats. *Journal of Molecular Endocrinology* **53** 237–246. (<https://doi.org/10.1530/JME-14-0063>)
- Kurtz M, Capobianco E, Careaga V, Martinez N, Mazzucco MB, Maier M & Jawerbaum A 2014b Peroxisome proliferator-activated receptor ligands regulate lipid content, metabolism, and composition in fetal lungs of diabetic rats. *Journal of Endocrinology* **220** 345–359. (<https://doi.org/10.1530/JOE-13-0362>)
- Lacroix M, Kina E & Hivert MF 2013 Maternal/fetal determinants of insulin resistance in women during pregnancy and in offspring over life. *Current Diabetes Reports* **13** 238–244. (<https://doi.org/10.1007/s11892-012-0360-x>)
- Lalloyer F, Vandewalle B, Percevault F, Torpier G, Kerr-Conte J, Oosterveer M, Paumelle R, Fruchart JC, Kuipers F, Pattou F, *et al.* 2006 Peroxisome proliferator-activated receptor  $\alpha$  improves pancreatic adaptation to insulin resistance in obese mice and reduces lipotoxicity in human islets. *Diabetes* **55** 1605–1613. (<https://doi.org/10.2337/db06-0016>)
- Laybutt DR, Sharma A, Sgroi DC, Gaudet J, Bonner-Weir S & Weir GC 2002 Genetic regulation of metabolic pathways in beta-cells disrupted by hyperglycemia. *Journal of Biological Chemistry* **277** 10912–10921. (<https://doi.org/10.1074/jbc.M111751200>)
- Marciniak A, Patro-Malysza J, Kimber-Trojnar Z, Marciniak B & Oleszczuk J 2017 Fetal programming of the metabolic syndrome. *Taiwanese Journal of Obstetrics & Gynecology* **56** 133–138.
- Martínez N, Capobianco E, White V, Pustovrh MC, Higa R & Jawerbaum A 2008 Peroxisome proliferator-activated receptor alpha activation regulates lipid metabolism in the fetoplacental unit from diabetic rats. *Reproduction* **136** 95–103. (<https://doi.org/10.1530/REP-08-0028>)
- Martínez N, Kurtz M, Capobianco E, Higa R, White V & Jawerbaum A 2011 PPAR $\alpha$  agonists regulate lipid metabolism and nitric oxide production and prevent placental overgrowth in term placentas from diabetic rats. *Journal of Molecular Endocrinology* **47** 1–12. (<https://doi.org/10.1530/JME-10-0173>)
- Martinez N, Sosa M, Higa R, Fornes D, Capobianco E & Jawerbaum A 2012 Dietary treatments enriched in olive and safflower oils regulate seric and placental matrix metalloproteinases in maternal diabetes. *Placenta* **33** 8–16. (<https://doi.org/10.1016/j.placenta.2011.10.015>)
- Mauvais-Jarvis F 2018 Gender differences in glucose homeostasis and diabetes. *Physiology and Behavior* **187** 20–23. (<https://doi.org/10.1016/j.physbeh.2017.08.016>)
- Moibi JA, Gupta D, Jetton TL, Peshavaria M, Desai R & Leahy JL 2007 Peroxisome proliferator-activated receptor- $\gamma$  regulates expression of PDX-1 and NKX6.1 in INS-1 cells. *Diabetes*. (<https://doi.org/10.2337/db06-0948>)
- Nguyen KT, Tajmir P, Lin CH, Liadis N, Zhu X, Eweida M, Tolaskaran G, Cai F, Wang R, Kitamura T, *et al.* 2006 Essential role of pten in body size determination and pancreatic beta-cell

- homeostasis in vivo. *Society* **26** 4511–4518. (<https://doi.org/10.1128/MCB.00238-06>)
- Ojha S, Robinson L, Symonds ME & Budge H 2013 Suboptimal maternal nutrition affects offspring health in adult life. *Early Human Development* **89** 909–913. (<https://doi.org/10.1016/j.earlhumdev.2013.08.022>)
- Petrik J, Reusens B, Arany E, Remacle C, Coelho C, Hoet JJ & Hill DJ 1999 A low protein diet alters the balance of islet cell replication and apoptosis in the fetal and neonatal rat. *Endocrinology* **140** 4861–4873. (<https://doi.org/10.1210/en.140.10.4861>)
- Ravnskjaer K, Frigerio F, Boergesen M, Nielsen T, Maechler P & Mandrup S 2010 PPAR $\delta$  is a fatty acid sensor that enhances mitochondrial oxidation in insulin-secreting cells and protects against fatty acid-induced dysfunction. *Journal of Lipid Research* **51** 1370–1379. (<https://doi.org/10.1194/jlr.M001123>)
- Rees WD, McNeil CJ & Maloney CA 2008 The roles of PPARs in the fetal origins of metabolic health and disease. *PPAR Research* **2008** 459030. (<https://doi.org/10.1155/2008/459030>)
- Rosen ED, Kulkarni RN, Sarraf P, Ozcan U, Okada T, Hsu C-H, Eisenman D, Magnuson MA, Gonzalez FJ, Kahn CR, *et al.* 2003 Targeted elimination of peroxisome proliferator-activated receptor gamma in beta cells leads to abnormalities in islet mass without compromising glucose homeostasis. *Molecular and Cellular Biology* **23** 7222–7229. (<https://doi.org/10.1128/MCB.23.20.7222-7229.2003>)
- Ryan M 2000 Diabetes and the Mediterranean diet: a beneficial effect of oleic acid on insulin sensitivity, adipocyte glucose transport and endothelium-dependent vasoreactivity. *QJM* **93** 85–91. (<https://doi.org/10.1093/qjmed/93.2.85>)
- Schwingshackl L & Hoffmann G 2014 Monounsaturated fatty acids, olive oil and health status: a systematic review and meta-analysis of cohort studies. *Lipids in Health and Disease* **13** 1–15. (<https://doi.org/10.1186/1476-511X-13-154>)
- Sobngwi E, Boudou P, Mauvais-Jarvis F, Leblanc H, Velho G, Vexiau P, Porcher R, Hadjadj S, Pratley R, Tataranni PA, *et al.* 2003 Effect of a diabetic environment in utero on predisposition to type 2 diabetes. *Lancet* **361** 1861–1865. ([https://doi.org/10.1016/S0140-6736\(03\)13505-2](https://doi.org/10.1016/S0140-6736(03)13505-2))
- Vassiliou EK, Gonzalez A, Garcia C, Tadros JH, Chakraborty G & Toney JH 2009 Oleic acid and peanut oil high in oleic acid reverse the inhibitory effect of insulin production of the inflammatory cytokine TNF-both in vitro and in vivo systems. *Lipids in Health and Disease* **8** 25. (<https://doi.org/10.1186/1476-511X-8-25>)
- Wieser F, Waite L, Depoix C & Taylor RN 2008 PPAR action in human placental development and pregnancy and its complications. *PPAR Research* **2008** 527048. (<https://doi.org/10.1155/2008/527048>)
- Winzell MS, Wulff EM, Olsen GS, Sauerberg P, Gotfredsen CF & Åhrén B 2010 Improved insulin sensitivity and islet function after PPARdelta activation in diabetic db/db mice. *European Journal of Pharmacology* **626** 297–305. (<https://doi.org/10.1016/j.ejphar.2009.09.053>)
- Yang Y, Ren J, Tong Y, Hu Q, Tong N 2016 Protective role of PPAR delta in lipoapoptosis of pancreatic beta cells. *Lipids* **51** 1259–1268. (<https://doi.org/10.1007/s11745-016-4190-5>)
- Zhang X, Gaspard JP, Mizukami Y, Li J, Graeme-Cook F & Chung DC 2005 Overexpression of cyclin D1 in pancreatic  $\beta$ -cells in vivo results in islet hyperplasia without hypoglycemia. *Diabetes* **54** 712–719. (<https://doi.org/10.2337/diabetes.54.3.712>)

Received in final form 7 May 2020

Accepted 2 June 2020

Accepted Manuscript published online 2 June 2020