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THE PANCREATIC β -CELL AS A TARGET OF ESTROGENS AND
XENOESTROGENS: IMPLICATIONS FOR BLOOD GLUCOSE HOMEOSTASIS
AND DIABETES

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The estrogen receptor ER α is emerging as a key molecule involved in glucose and lipid metabolism. The main functions of pancreatic β -cells are the biosynthesis and release of insulin, the only hormone that can directly decrease blood glucose levels. Estrogen receptors ER α and ER β exist in β -cells. The role of ER β is still unknown, yet ER α plays an important role in the regulation of insulin biosynthesis, insulin secretion and β -cell survival. Activation of ER α by 17 β -estradiol (E2) and the environmental estrogen Bisphenol-A (BPA) promotes an increase of insulin biosynthesis through a non-classical estrogen-activated pathway that involves phosphorylation of ERK1/2. The activation of ER α by physiological concentrations of E2 may play an important role in the adaptation of the endocrine pancreas to pregnancy. However, if ER α is over stimulated by an excess of E2 or the action of an environmental estrogen such as BPA, it will produce an excessive insulin signaling. This may provoke insulin resistance in the liver and muscle, as well as β -cell exhaustion and therefore, it may contribute to the development of type II diabetes.

The role of the endocrine pancreas in blood glucose homeostasis

Blood glucose levels must be maintained within a precise range throughout the day, independently of dietary nutrient ingestion. This process, defined as blood glucose homeostasis involves a complex communication between different tissues, including the liver, skeletal muscle, adipose tissue, brain and the endocrine pancreas (Herman & Kahn, 2006; Rosen & Spiegelman, 2006; Fritsche *et al.*, 2008). During the fasting state, insulin remains at low levels because plasma glucose concentration is low. In this situation, the levels of the counter-regulatory hormones, glucagon, adrenaline and corticosteroids are increased to promote hepatic glucose production. In contrast, insulin, the only hormone in the body able to decrease blood glucose levels, is increased during the fed state. Insulin decreases blood glucose by promoting adipocyte and muscle glucose uptake, as well as by preventing the liver from producing glucose by suppressing glycogenolysis and gluconeogenesis (Fritsche *et al.*, 2008).

The endocrine cells of the pancreas are grouped in the islets of Langerhans, which constitute approximately 1 to 2% of the pancreas mass. Islets are distributed throughout the organ and in healthy human adults; their number reaches one million islets per pancreas. Each islet contains between 1000-3000 cells of five types, the most abundant are β -cells, which synthesize and release insulin and α -cells which synthesize and secrete glucagon. In a lower proportion, islets contain δ -cells and PP-cells that release somatostatin and pancreatic polypeptide respectively (Brissova *et al.*, 2005; Cabrera *et al.*, 2006). Recently, a small population of ghrelin-producing cells, named as epsilon-cells, has been identified (Prado *et al.*, 2004). The percentage of the different cell subpopulations and the islet cytoarchitecture vary between species. In rodent islets, β -cells are the most abundant, 60-80 % of the total number of cells; α -cells account for 15-20 %, while δ -cells are less than 10% and PP-cells about 1%. In rodents, β -cells are

in the core of the islets while non- β -cells are distributed in the periphery (Brissova *et al.*, 2005;Cabrera *et al.*, 2006). In human islets, the proportion of δ - and PP-cells is similar to rodent islets, but the percentage of α -cells is higher (35-45%) and the β -cell percentage is lower (55-65%). Moreover, α and β -cells are distributed evenly throughout the islet, suggesting that paracrine interactions between both types of cells may be more important in humans than in rodents (Brissova *et al.*, 2005;Cabrera *et al.*, 2006).

The main function of pancreatic β -cells is the biosynthesis and release of insulin. The rate of insulin biosynthesis is controlled by many signalling molecules including: neurotransmitters, hormones and nutrients, among which glucose is the most important. Normally, in response to short glucose stimulation, insulin biosynthesis is regulated by the increased translation of the preproinsulin transcript. After a prolonged glucose exposure, however, it is regulated via the insulin gene transcription (Orland *et al.*, 1985;Permutt & Rotwein, 1983;Poitout *et al.*, 2006). Both transcriptional and translational regulation of insulin biosynthesis is essential to maintain the intracellular stores of insulin on a long term basis.

The secretory response of β -cells depends on their electrical activity. This consists of oscillations of the membrane potential that range from electrically silent periods to depolarised plateaus on which Ca^{2+} -action potentials originate (Rorsman *et al.*, 2000). The classical stimulus-secretion coupling that drives insulin release involves the closure of K_{ATP} channels by increasing the intracellular ATP/ADP ratio (Ashcroft *et al.*, 1984) and diadenosine polyphosphates concentration (DPs) (Ripoll *et al.*, 1996) because of glucose metabolism. The K_{ATP} channels closure induces membrane depolarization that activates voltage-operated Ca^{2+} channels and Ca^{2+} influx (Valdeolmillos *et al.*, 1992).

Therefore, as a consequence of the oscillations in the membrane potential, a $[Ca^{2+}]_i$ oscillatory pattern is originated (Nadal *et al.*, 1999; Santos *et al.*, 1991; Valdeolmillos *et al.*, 1989), which triggers a pulsatile insulin secretion (Barbosa *et al.*, 1998; Gilon *et al.*, 1993; Dyachok *et al.*, 2008).

Estrogens, estrogen receptors and blood glucose homeostasis

The evolution of type 2 diabetes requires the presence of defects in both insulin secretion (β -cell dysfunction) and insulin action (insulin resistance). Both defects have a recognized genetic background as well as an environmental component, where the lack of exercise and obesity play important roles. Although it is not usually emphasized, during the prediabetic phase, when insulin resistance has developed, the β -cell hyper secretes insulin to maintain normal blood glucose levels provoking hyperinsulinaemia (McGarry, 2002). This hyperinsulinemia may produce an excess of insulin signaling in the liver, kidneys and ovaries, leading to hypertriglyceridemia, increased sodium retention, hypertension, and hyperandrogenism (Biddinger & Kahn, 2006).

Estrogens are hormones to be considered in blood glucose homeostasis, although in which conditions they exert a beneficial or detrimental action is still a matter of debate. A change in blood estrogens occurs during pregnancy as well as during the menstrual cycle in humans or the estrous cycle in rodents. At those physiological levels, E2 is thought to be involved in maintaining normal insulin sensitivity and to be beneficial for β -cell function (Livingstone & Collison, 2002; Louet *et al.*, 2004). However, E2 levels above or below the physiological range may promote insulin resistance and type II diabetes (Ding *et al.*, 2007; Godsland, 2005; Gonzalez *et al.*, 2003; Livingstone & Collison, 2002).

Evidence that high E2 concentrations are detrimental for blood glucose homeostasis has existed for a long time. In humans, the most consistent effects of oral contraceptives and estrogen replacement therapy (HRT) are lowering fasting plasma glucose and worsening glucose tolerance. However, basal insulin levels are unchanged or slightly reduced, whereas glucose-stimulated insulin release is enhanced (Godsland, 2005). This is not only seen in humans but also in male mice exposed to E2 (100 µg/kg/day) for 4 days (Alonso-Magdalena *et al.*, 2006;Ropero *et al.*, 2008a). Therefore, an excess of estrogens, such as in oral contraceptives or HRT with high estrogen doses, is related to insulin resistance (Godsland, 2005).

Low levels of estrogen because of ovariectomy or menopause are associated with impaired glucose tolerance and insulin resistance. This effects are counteracted in both situations by physiological estrogen replacement (Godsland, 1996). It has been reported that estrogen function deficiency in men, due to the absence of ER α or aromatase, results in impaired glucose metabolism. All patients with aromatase deficiency, due to a point mutation of the aromatase gene, have glucose metabolism impairment and insulin resistance (Zirilli *et al.*, 2008). Similar abnormalities were found in aromatase-deficient (ArKO) mice (Jones *et al.*, 2000). In the only described case of a congenital estrogen deficiency due to an inactivating mutation of the ER α gene in a human, the man had glucose intolerance and hyperinsulinaemia, among other pathologies. In addition, he had a clear hormonal resistance syndrome, consistent of high serum E2, estrone, FSH and LH levels, although testosterone levels were normal (Smith *et al.*, 1994;Zirilli *et al.*, 2008). In humans it has been shown that genetic polymorphism of ER α gene is associated with type II diabetes and metabolic syndrome (Gallagher *et al.*, 2007). It has been demonstrated that estrogen receptors ER α and ER β have both been involved in energy balance and blood glucose homeostasis (Ropero *et al.*, 2008b). Nevertheless,

evidence points to ER α as the main mediator. ER α knockout mice (ER α KO) are obese and insulin resistant (Heine *et al.*, 2000). ER α has been involved in glucose metabolism in different tissues including skeletal muscle, adipose tissue, liver, brain and endocrine pancreas (Barros *et al.*, 2006;Ropero *et al.*, 2008b).

GLUT4 is the major insulin-stimulated glucose transporter and the main rate-limiting step in insulin-stimulated glucose uptake in muscle and adipocytes. GLUT4 expression in the skeletal muscle cell membrane depends on ER α . It is extremely reduced in ER α KO mice, unaffected in ER β KO mice and elevated in ArKO mice (Barros *et al.*, 2006).

The estrogen receptor ER α is also involved in modulating hepatic insulin sensitivity, but the ER β is not. Actually, ER α KO mice have severe hepatic insulin resistance as well as a concomitant alteration of glucose uptake by skeletal muscle (Bryzgalova *et al.*, 2006). Additionally, estrogens control the distribution of body fat and adipose tissue metabolism, involving both ER α and ER β (Cooke *et al.*, 2001;Couse & Korach, 1999;Naaz *et al.*, 2002;Penza *et al.*, 2006). Indeed, it is known that estrogens can regulate the amount of white adipose tissue (WAT) both in females and males. It has been demonstrated that the absence of ER α produces adipocyte hyperplasia and hypertrophy in WAT, but not in brown adipocyte tissue (BAT). This is accompanied by insulin resistance and glucose intolerance (Cooke *et al.*, 2001;Heine *et al.*, 2000). Human studies also suggest that both receptors may play an important role in fat metabolism and obesity. The ratio ER α /ER β seems to be associated with obesity as well as with the serum level and the production of leptin in omental adipose tissue in women (Shin *et al.*, 2007). In the brain, the disruption of the ER α in the ventromedial nucleus of the hypothalamus leads to weight gain, increased visceral adiposity, hyperphagia, hyperglycaemia and impaired energy expenditure in female mice (Musatov *et al.*, 2007).

In addition, ER β has been shown to have anorectic effects mediated via the central nervous system (Liang *et al.*, 2002). Recently, it has been demonstrated that ER β is important for adiposity regulation when mice are challenged with a high fat diet (Foryst-Ludwig *et al.*, 2008).

Although ER α and ER β represent the main link between estrogens and metabolism, other feasible players currently emerging are liver X receptors (LXRs). It is already known that estrogens can regulate LXRs in metabolic tissues. Lundholm *et al.* 2004, demonstrated that 17 β -estradiol can decrease mRNA expression of LXR α . Furthermore they show a direct down-regulation of the LXR α promoter by estrogen.

LXRs are well recognized as important regulators of cholesterol homeostasis as well as modulators of lipid and carbohydrate metabolism. Accordingly, it has been shown that the administration of synthetic LXR agonists to a mouse model of obesity and insulin resistance improves glucose tolerance (Laffitte *et al.*, 2003). This was attributed to a coordinate transcriptional regulation of genes involved in glucose metabolism in both the liver and the adipose tissue. In the liver, the activation of LXRs leads to the suppression of the gluconeogenic program. However, in white adipose tissue, the expression of the insulin-sensitive glucose transporter (GLUT4), which promotes glucose uptake, is upregulated after LXR activation (Dalen *et al.*, 2003).

Besides its action on peripheral tissues, a novel role for LXR in the pancreas has recently been described. The addition of the LXR agonist T09011317 to pancreatic islets results in enhanced glucose-dependent insulin secretion (Efanov *et al.*, 2004). On the other hand, the absence of LXR β in mice leads to glucose intolerance and to an accumulation of lipid droplets in pancreatic islets, attributed to a possible disturbance in cholesterol efflux due to a decreased expression of ABC transporters (Gerin *et al.*, 2005).

The role of the estrogen receptor ER α in the pancreatic β -cell

As described in the above paragraph, the role of estrogen receptors in glucose metabolism has been mainly studied in tissues other than the endocrine pancreas. In order to understand how estrogens affect the adaptation of β -cells to physiological situations such as pregnancy and how they are involved in gender functional differences in the endocrine pancreas (Karlsson *et al.*, 2002), it is essential to investigate the role of ER α and ER β in this cellular system.

In vivo experiments demonstrated that adult male mice treated with E2 100 μ g/kg/day for 4 days presented an altered glucose tolerance and were insulin resistant. In addition, these animals presented a postprandial hyperinsulinaemia (Alonso-Magdalena *et al.*, 2006; Ropero *et al.*, 2008b). When islets from treated animals were analyzed, they presented higher insulin content together with an enhanced insulin release in response to increasing glucose concentrations (Alonso-Magdalena *et al.*, 2006). These may result from an adaptation of islets to the insulin resistance noted in these animals or to a direct effect of E2 on β -cell insulin content or both.

In order to investigate whether estrogens directly regulate insulin biosynthesis, we studied pancreatic insulin content and insulin secretion in isolated islets from male mice cultured in the presence of estrogens. We obtained that physiological concentrations of E2 (100pM-10nM) together with a stimulatory glucose concentration 11mM, increased pancreatic insulin content in an inverted-U dose dependent manner (Alonso-Magdalena *et al.*, 2008). This increase in pancreatic insulin content was not due to an enhanced β -cell mass, since the islet area did not change and no BrdU incorporation occurred during the estrogen treatment. Moreover, real time PCR experiments demonstrated that E2 treatment increased insulin mRNA. Therefore, E2 increases insulin gene expression and insulin biosynthesis, incrementing pancreatic insulin content. In addition, insulin

secretion in response to glucose was enhanced as previously described (Adachi *et al.*, 2005).

In both *in vitro* and *in vivo* studies, E2 actions were blocked by the antiestrogen ICI182,780 suggesting that either ER α or ER β are involved (Adachi *et al.*, 2005; Alonso-Magdalena *et al.*, 2006; Alonso-Magdalena *et al.*, 2008). The existence of estrogen receptors in β -cells has not been extensively studied until now. Nonetheless, it has been demonstrated that both ER α and ER β were expressed in mouse β -cells in primary culture by immunocytochemistry using a battery of antibodies against both receptors (Nadal *et al.*, 2000). In mice expressing human amyloid peptide, only a 58kDa form of ER α was detected, but ER β was not (Geisler *et al.*, 2002). In a recent study, the full-length 67kDa isoform was expressed in mouse and MIN6 cells, while a smaller 58kDa form was only present in islets (Le May *et al.*, 2006). We demonstrated by RT-PCR and immunocytochemistry that both ER α and ER β were present in mouse islets of Langerhans (Alonso-Magdalena *et al.*, 2008). The use of ER α and ER β agonists as well as islets from ER α KO and ER β KO mice demonstrated that E2 action on insulin biosynthesis is mediated by the estrogen receptor ER α (Alonso-Magdalena *et al.*, 2008). Remarkably, the E2-induced increase of insulin biosynthesis was imitated by bisphenol A (BPA) at exactly the same doses of E2 and following the same pathway.

Besides the role that ER α plays in the regulation of pancreatic insulin content, it has been demonstrated that it plays a key function in pancreatic β -cell survival after an oxidative stress treatment (Le May *et al.*, 2006). In this work, a single dose of streptozotocin (STZ) induced a loss of β -cells and pancreas insulin content in wild type males as well as females. In ArKO $^{-/-}$ mice the same STZ treatment provoked β -cell destruction in both genders, an effect that was suppressed by E2 treatment. These authors demonstrated that the protective effect of E2 is via ER α . In the rat, however,

diabetes development in response to STZ treatment is more severe in females than in males (Vital *et al.*, 2006). After 4 weeks of diabetes, females show less and smaller pancreatic islets, and less serum insulin than control females and diabetic males; indeed diabetic females have higher blood glucose values and lower survival rates than diabetic males (Vital *et al.*, 2006). This is in accordance with the action of testosterone in protecting β -cells from STZ-induced apoptosis (Morimoto *et al.*, 2005). More research is warranted in this area to solve the gender differences that apparently exist between mice and rats.

E2 and BPA are equally effective through a non-classical estrogen-activated pathway

BPA is an organic compound widely recognised as an important endocrine disruptor chemical (EDC). This term refers to all those chemicals able to mimic or interfere with the normal actions of endocrine hormones. Although research was first focused only on reproductive parameters and potential carcinogenic effects, nowadays, many studies point out that EDC may affect multiple organ systems including the cardiovascular and neuro-endocrine systems. Moreover, recent interest has emerged from the idea of an association between EDCs and the metabolic syndrome. Regarding this issue, an increasing number of studies reports that exposure to chemicals during critical periods of differentiation, at low environmentally-relevant doses, alters developmental programming, resulting in obesity (Newbold *et al.*, 2008). Furthermore, some persistent organic pollutants (POPs) have been reported to be linked to the prevalence of type 2 diabetes and insulin resistance (Lee *et al.*, 2007). Remarkably, there exists an epidemiological link between BPA concentration in urine and type 2 diabetes,

cardiovascular disease and liver enzyme abnormalities in a representative sample of adult US population (Lang *et al.*, 2008; vom Saal & Myers, 2008).

We have contributed to this hypothesis by analyzing the effects of EDCs on an essential tissue in glucose homeostasis, the endocrine pancreas, and reported the high sensitivity of this organ to BPA. Indeed, we have observed that BPA can mimic E2 effects with the same potency (Alonso-Magdalena *et al.*, 2006; Alonso-Magdalena *et al.*, 2008; Ropero *et al.*, 2008b).

The equal potency of both E2 and BPA in insulin biosynthesis regulation was a paradox. In the past, BPA was considered a “weak” estrogen because of its low binding affinity to both ER α and ER β (Kuiper *et al.*, 1997; Kuiper *et al.*, 1998), as well as for having a low transcriptional activity through these ERE binding receptors (Sheeler *et al.*, 2000). In our work, however, both E2 and BPA were equally effective on insulin content up-regulation even though that the mouse insulin gene does not contain an ERE. Examples of low dose effects of BPA have been reported in a wide variety of tissues and cell types (vom Saal & Hughes, 2005; Wetherill *et al.*, 2007), although the mechanism of action to explain them are still unclear. One explanation could be that BPA may act via ER α through mechanisms other than binding to ERE. For instance, it may act through other transcription factors binding to their respective response elements (Dahlman-Wright *et al.*, 2006). In addition, it has been demonstrated that extra-nuclear ER α can activate protein kinases (Giretti *et al.*, 2008; Migliaccio *et al.*, 1996; Simoncini *et al.*, 2000). Contrary to the results shown by Le May *et al.* (2006) that exclusively found ER α in β -cell nuclei, our data indicate that in β -cells, ER α is located inside and outside the nucleus (Alonso-Magdalena *et al.*, 2008). Furthermore, we found that the ER α agonist PPT rapidly increased the phosphorylation of ERK1/2 in pancreatic β -cell cytoplasm, with a maximal effect after 15 minutes of incubation (Alonso-Magdalena *et*

al., 2008). The inhibition of ERK1/2 phosphorylation by PD98059 abrogated the action of PPT, E2 and BPA on islet insulin content (Alonso-Magdalena *et al.*, 2008). The kinase Src may play a role as well, since the Src inhibitor PP1 greatly diminished the stimulatory effect of BPA on islet insulin content. Our results demonstrate that ERK1/2 mediate the ER α -induced amplification of insulin biosynthesis (Figure 1). Additionally, estrogens and xenoestrogens act through other mechanisms independently of ER α and ER β to increase insulin secretion in a rapid manner *in vitro* and *in vivo* (Nadal *et al.*, 2000;Nadal *et al.*, 1998;Nadal *et al.*, 2004;Ripoll *et al.*, 2008;Alonso-Magdalena *et al.*, 2006).

Physiological and pathophysiological consequences of ER α up-regulation of insulin

The action of ER α on insulin biosynthesis has important physiological implications. During pregnancy, islets adapt to the increased demand for insulin undergoing major changes in their structure and function. Among these changes, the increase of insulin synthesis is of great importance (Bone & Taylor, 1976;Green *et al.*, 1973). Up until now, this effect has been attributed to the activity of lactogenic hormones (Parsons *et al.*, 1992;Sorenson *et al.*, 1993). However, the E2-induced up-regulation of insulin biosynthesis may be another mechanism that, together with placental lactogen and prolactin, participates in the adaptation of insulin production to counteract the increased metabolic demand of pregnancy. It is plausible that, during pregnancy, ER α integrates information from E2, glucose and other nutrients in the blood to regulate insulin gene expression and, therefore, contributes to the maintenance of insulin and glucose homeostasis. On the contrary, if this estrogenic action occurs at an inappropriate time, or at doses not within physiological levels, it may cause adverse effects such as insulin resistance. This may happen when there is an exposure to an environmental estrogen, such as BPA, which causes postprandial hyperinsulinemia and insulin resistance in

healthy male mice (Alonso-Magdalena *et al.*, 2006). An excess of ER α action mediated by an environmental estrogen such as BPA will provoke an increase in pancreatic β -cell content and secretion, both *in vivo* and *in vitro*, overstimulating β -cells (Figure 2). Excessive insulin signaling in the liver or endothelium produces dyslipidemia and in fat, it produces obesity, glucose intolerance, and dyslipidemia (Biddinger & Kahn, 2006). In addition, an excessive insulin signaling may provoke insulin resistance in the liver and muscle (Ueno *et al.*, 2005) as well as β -cell exhaustion (Aston-Mourney *et al.*, 2008) and therefore, contributing to the development of type II diabetes (Figure 2).

Concluding remarks

Estrogen receptors are key molecules involved in blood glucose homeostasis. Particularly, ER α in β -cell has a crucial role in increasing proinsulin biosynthesis in response to physiological concentrations of E2. This may be an important mechanism for the islet of Langerhans to adapt to the high demand of insulin during pregnancy.

This mechanism, however, can be activated as well in male mice by the widespread endocrine disruptor BPA, when there is no physiological need for an increase in insulin biosynthesis and secretion. Moreover, *in vivo* BPA treatment at environmentally relevant doses induces insulin resistance in healthy adult male mice. Is there a role for environmental estrogens such as BPA in the aetiology of type-2 diabetes? It has been demonstrated that type 2 diabetes only develops in insulin resistant subjects with the onset of β -cell dysfunction. Islet susceptibility to dysfunction depends on genetic and environmental factors, including intrauterine and early life environment (Prentki & Nolan, 2006). The actions of environmental estrogens in uterus and early life on the function of the islet of Langerhans are still unknown and it is an important area of research to explore. In adult humans, however, epidemiological evidence exist that point

to BPA as an important environmental risk factor in the development of type 2 diabetes (Lang *et al.*, 2008). In addition, there are causal links between BPA exposure and insulin resistance (Alonso-Magdalena *et al.*, 2006), alteration of insulin biosynthesis and secretion in β -cells in adult male mice (Alonso-Magdalena *et al.*, 2008) and decrease of adiponectin in human adipocytes (Hugo *et al.*, 2008). Insulin resistance and decrease of adiponectin should contribute to the development of type 2 diabetes, especially in subjects with a genetic susceptibility to β -cell failure. The BPA-induced increase in insulin biosynthesis and secretion produces overstimulation of β -cells. This excessive demand, when prolonged in time, may produce endoplasmic reticulum stress, particularly when β -cell mass is not altered, contributing to β -cell failure. Therefore, although the main causes of β -cell failure in type 2 diabetes are overnutrition and lack of exercise, environmental estrogens, in particular BPA, are strong candidates to exacerbate and accelerate the development of type 2 diabetes.

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REFERENCES

- Adachi, T., Yasuda, K., Mori, C., Yoshinaga, M., Aoki, N., Tsujimoto, G., & Tsuda, K. 2005. Promoting insulin secretion in pancreatic islets by means of bisphenol A and nonylphenol via intracellular estrogen receptors. *Food and Chemical Toxicology* 43, 713-719.
- Alonso-Magdalena, P., Morimoto, S., Ripoll, C., Fuentes, E., & Nadal, A. 2006. The estrogenic effect of bisphenol A disrupts pancreatic beta-cell function in vivo and induces insulin resistance. *Environ. Health Perspect.* 114, 106-112.

- Alonso-Magdalena, P., Ropero, A. B., Carrera, M. P., Cederroth, C. R., Baquie, M., Gauthier, B. R., Nef, S., Stefani, E., & Nadal, A. 2008. Pancreatic insulin content regulation by the estrogen receptor ER alpha. *PLoS.ONE*. 3, e2069.
- Ashcroft, F. M., Harrison, D. E., & Ashcroft, S. J. 1984. Glucose induces closure of single potassium channels in isolated rat pancreatic beta-cells. *Nature* 312, 446-448.
- Aston-Mourney, K., Proietto, J., Morahan, G., & Andrikopoulos, S. 2008. Too much of a good thing: why it is bad to stimulate the beta cell to secrete insulin. *Diabetologia* 51, 540-545.
- Barbosa, R. M., Silva, A. M., Tome, A. R., Stamford, J. A., Santos, R. M., & Rosario, L. M. 1998. Control of pulsatile 5-HT/insulin secretion from single mouse pancreatic islets by intracellular calcium dynamics. *J. Physiol.* 510, 135-143.
- Barros, R. P., Machado, U. F., & Gustafsson, J. A. 2006. Estrogen receptors: new players in diabetes mellitus. *Trends Mol. Med.* 12, 425-431.
- Biddinger, S. B. & Kahn, C. R. 2006. From mice to men: insights into the insulin resistance syndromes. *Annu. Rev. Physiol.* 68, 123-158.
- Bone, A. J. & Taylor, K. W. 1976. Metabolic adaptation to pregnancy shown by increased biosynthesis of insulin in islets of Langerhans isolated from pregnant rat. *Nature* 262, 501-502.
- Brissova, M., Fowler, M. J., Nicholson, W. E., Chu, A., Hirshberg, B., Harlan, D. M., & Powers, A. C. 2005. Assessment of human pancreatic islet architecture and composition by laser scanning confocal microscopy. *J. Histochem. Cytochem.* 53, 1087-1097.
- Bryzgalova, G., Gao, H., Ahren, B., Zierath, J. R., Galuska, D., Steiler, T. L., Dahlman-Wright, K., Nilsson, S., Gustafsson, J. A., Efendic, S., & Khan, A. 2006. Evidence that oestrogen receptor-alpha plays an important role in the regulation of glucose homeostasis in mice: insulin sensitivity in the liver. *Diabetologia* 49, 588-597.
- Cabrera, O., Berman, D. M., Kenyon, N. S., Ricordi, C., Berggren, P. O., & Caicedo, A. 2006. The unique cytoarchitecture of human pancreatic islets has implications for islet cell function. *Proc. Natl. Acad. Sci. U.S.A* 103, 2334-2339.
- Cooke, P. S., Heine, P. A., Taylor, J. A., & Lubahn, D. B. 2001. The role of estrogen and estrogen receptor-alpha in male adipose tissue. *Mol. Cell Endocrinol.* 178, 147-154.
- Couse, J. F. & Korach, K. S. 1999. Estrogen receptor null mice: what have we learned and where will they lead us? *Endocr. Rev.* 20, 358-417.
- Dahlman-Wright, K., Cavailles, V., Fuqua, S. A., Jordan, V. C., Katzenellenbogen, J. A., Korach, K. S., Maggi, A., Muramatsu, M., Parker, M. G., & Gustafsson, J. A. 2006. International Union of Pharmacology. LXIV. Estrogen receptors. *Pharmacol. Rev.* 58, 773-781.

- Dalen, K. T., Ulven, S. M., Bamberg, K., Gustafsson, J. A., & Nebb, H. I. 2003. Expression of the insulin-responsive glucose transporter GLUT4 in adipocytes is dependent on liver X receptor alpha. *J. Biol. Chem.* 278, 48283-48291.
- Ding, E. L., Song, Y., Manson, J. E., Rifai, N., Buring, J. E., & Liu, S. 2007. Plasma sex steroid hormones and risk of developing type 2 diabetes in women: a prospective study. *Diabetologia* 50, 2076-2084.
- Dyachok, O., Idevall-Hagren, O., Sagetorp, J., Tian, G., Wuttke, A., Arriemerlou, C., Akusjarvi, G., Gylfe, E., & Tengholm, A. 2008. Glucose-induced cyclic AMP oscillations regulate pulsatile insulin secretion. *Cell Metab.* 8, 26-37.
- Efanov, A. M., Sewing, S., Bokvist, K., & Gromada, J. 2004. Liver X receptor activation stimulates insulin secretion via modulation of glucose and lipid metabolism in pancreatic beta-cells. *Diabetes* 53 Suppl 3, S75-S78.
- Foryst-Ludwig, A., Clemenz, M., Hohmann, S., Hartge, M., Sprang, C., Frost, N., Krikov, M., Bhanot, S., Barros, R., Morani, A., Gustafsson, J. A., Unger, T., & Kintscher, U. 2008. Metabolic actions of estrogen receptor beta (ERbeta) are mediated by a negative cross-talk with PPARgamma. *PLoS.Genet.* 4, e1000108.
- Fritsche, L., Weigert, C., Haring, H. U., & Lehmann, R. 2008. How insulin receptor substrate proteins regulate the metabolic capacity of the liver--implications for health and disease. *Curr. Med. Chem.* 15, 1316-1329.
- Gallagher, C. J., Langefeld, C. D., Gordon, C. J., Campbell, J. K., Mychaleckyj, J. C., Bryer-Ash, M., Rich, S. S., Bowden, D. W., & Sale, M. M. 2007. Association of the estrogen receptor-alpha gene with the metabolic syndrome and its component traits in African-American families: the Insulin Resistance Atherosclerosis Family Study. *Diabetes* 56, 2135-2141.
- Geisler, J. G., Zawalich, W., Zawalich, K., Lakey, J. R., Stukenbrok, H., Milici, A. J., & Soeller, W. C. 2002. Estrogen can prevent or reverse obesity and diabetes in mice expressing human islet amyloid polypeptide. *Diabetes* 51, 2158-2169.
- Gerin, I., Dolinsky, V. W., Shackman, J. G., Kennedy, R. T., Chiang, S. H., Burant, C. F., Steffensen, K. R., Gustafsson, J. A., & MacDougald, O. A. 2005. LXRbeta is required for adipocyte growth, glucose homeostasis, and beta cell function. *J. Biol. Chem.* 280, 23024-23031.
- Gilon, P., Shepherd, R. M., & Henquin, J. C. 1993. Oscillations of secretion driven by oscillations of cytoplasmic Ca²⁺ as evidences in single pancreatic islets. *J. Biol.Chem.* 268, 22265-22268.
- Giretti, M. S., Fu, X. D., De Rosa, G., Sarotto, I., Baldacci, C., Garibaldi, S., Mannella, P., Biglia, N., Sismondi, P., Genazzani, A. R., & Simoncini, T. 2008. Extra-nuclear signalling of estrogen receptor to breast cancer cytoskeletal remodelling, migration and invasion. *PLoS.ONE.* 3, e2238.
- Godsland, I. F. 1996. The influence of female sex steroids on glucose metabolism and insulin action. *J. Intern. Med. Suppl.* 738, 1-60.

- Godsland, I. F. 2005. Oestrogens and insulin secretion. *Diabetologia* 48, 2213-2220.
- Gonzalez, C., Alonso, A., Diaz, F., & Patterson, A. M. 2003. Dose- and time-dependent effects of 17beta-oestradiol on insulin sensitivity in insulin-dependent tissues of rat: implications of IRS-1. *J. Endocrinol.* 176, 367-379.
- Green, I. C., Howell, S. L., Montague, W., & Taylor, K. W. 1973. Regulation of insulin release from isolated islets of Langerhans of the rat in pregnancy. The role of adenosine 3':5'-cyclic monophosphate. *Biochem. J.* 134, 481-487.
- Heine, P. A., Taylor, J. A., Iwamoto, G. A., Lubahn, D. B., & Cooke, P. S. 2000. Increased adipose tissue in male and female estrogen receptor-alpha knockout mice. *Proc. Natl. Acad. Sci. U.S.A* 97, 12729-12734.
- Herman, M. A. & Kahn, B. B. 2006. Glucose transport and sensing in the maintenance of glucose homeostasis and metabolic harmony. *J. Clin. Invest.* 116, 1767-1775.
- Hugo, E. R., Brandebourg, T. D., Woo, J. G., Loftus, J., Alexander, J. W., & Ben-Jonathan, N. 2008. Bisphenol A at Environmentally Relevant Doses Inhibits Adiponectin Release from Human Adipose Tissue Explants and Adipocytes. *Environ. Health Perspect.* doi:10.1289/ehp.11537 [Online 14 August 2008].
- Jones, M. E. E., Thorburn, A. W., Britt, K. L., Hewitt, K. N., Wreford, N. G., Proietto, J., Oz, O. K., Leury, B. J., Robertson, K. M., Yao, S., & Simpson, E. R. 2000. Aromatase-deficient (ArKO) mice have a phenotype of increased adiposity. *Proc. Natl. Acad. Sci. U.S.A.* 97, 12735-12740.
- Karlsson, S., Scheurink, A. J., & Ahren, B. 2002. Gender difference in the glucagon response to glucopenic stress in mice. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 282, R281-R288.
- Kuiper, G. G., Carlsson, B., Grandien, K., Enmark, E., Haggblad, J., Nilsson, S., & Gustafsson, J. A. 1997. Comparison of the ligand binding specificity and transcript tissue distribution of estrogen receptors alpha and beta. *Endocrinology* 138, 863-870.
- Kuiper, G. G., Lemmen, J. G., Carlsson, B., Corton, J. C., Safe, S. H., van der Saag, P. T., van der, B. B., & Gustafsson, J. A. 1998. Interaction of estrogenic chemicals and phytoestrogens with estrogen receptor beta. *Endocrinology* 139, 4252-4263.
- Laffitte, B. A., Chao, L. C., Li, J., Walczak, R., Hummasti, S., Joseph, S. B., Castrillo, A., Wilpitz, D. C., Mangelsdorf, D. J., Collins, J. L., Saez, E., & Tontonoz, P. 2003. Activation of liver X receptor improves glucose tolerance through coordinate regulation of glucose metabolism in liver and adipose tissue. *Proc. Natl. Acad. Sci. U.S.A.* 100, 5419-5424.
- Lang, I. A., Galloway, T. S., Scarlett, A., Henley, W. E., Depledge, M., Wallace, R. B., & Melzer, D. 2008. Association of urinary bisphenol A concentration with medical disorders and laboratory abnormalities in adults. *JAMA: The Journal of the American Medical Association* 300, 1303-1310.

- Le May, C., Chu, K., Hu, M., Ortega, C. S., Simpson, E. R., Korach, K. S., Tsai, M. J., & Mauvais-Jarvis, F. 2006. Estrogens protect pancreatic beta-cells from apoptosis and prevent insulin-deficient diabetes mellitus in mice. *Proc. Natl. Acad. Sci. U.S.A.* 103, 9232-9237.
- Lee, D. H., Lee, I. K., Porta, M., Steffes, M., & Jacobs, D. R., Jr. 2007. Relationship between serum concentrations of persistent organic pollutants and the prevalence of metabolic syndrome among non-diabetic adults: results from the National Health and Nutrition Examination Survey 1999-2002. *Diabetologia* 50, 1841-1851.
- Liang, Y. Q., Akishita, M., Kim, S., Ako, J., Hashimoto, M., Iijima, K., Ohike, Y., Watanabe, T., Sudoh, N., Toba, K., Yoshizumi, M., & Ouchi, Y. 2002. Estrogen receptor beta is involved in the anorectic action of estrogen. *Int. J. Obes. Relat. Metab. Disord.* 26, 1103-1109.
- Livingstone, C. & Collison, M. 2002. Sex steroids and insulin resistance. *Clin. Sci (Lond)* 102, 151-166.
- Louet, J. F., LeMay, C., & Mauvais-Jarvis, F. 2004. Antidiabetic actions of estrogen: insight from human and genetic mouse models. *Curr. Atheroscler. Rep.* 6, 180-185.
- McGarry, J. D. 2002. Banting lecture 2001: dysregulation of fatty acid metabolism in the etiology of type 2 diabetes. *Diabetes* 51, 7-18.
- Migliaccio, A., Di Domenico, M., Castoria, G., de Falco, A., Bontempo, P., Nola, E., & Auricchio, F. 1996. Tyrosine kinase/p21ras/MAP-kinase pathway activation by estradiol- receptor complex in MCF-7 cells. *EMBO J.* 15, 1292-300.
- Morimoto, S., Mendoza-Rodriguez, C. A., Hiriart, M., Larrieta, M. E., Vital, P., & Cerbon, M. A. 2005. Protective effect of testosterone on early apoptotic damage induced by streptozotocin in rat pancreas. *J. Endocrinol.* 187, 217-224.
- Musatov, S., Chen, W., Pfaff, D. W., Mobbs, C. V., Yang, X. J., Clegg, D. J., Kaplitt, M. G., & Ogawa, S. 2007. Silencing of estrogen receptor alpha in the ventromedial nucleus of hypothalamus leads to metabolic syndrome. *Proc. Natl. Acad. Sci. U.S.A.* 104, 2501-2506.
- Naaz, A., Zakroczymski, M., Heine, P., Taylor, J., Saunders, P., Lubahn, D., & Cooke, P. S. 2002. Effect of ovariectomy on adipose tissue of mice in the absence of estrogen receptor alpha (ERalpha): a potential role for estrogen receptor beta (ERbeta). *Horm. Metab. Res.* 34, 758-763.
- Nadal, A., Quesada, I., & Soria, B. 1999. Homologous and heterologous asynchronicity between identified alpha-, beta- and delta-cells within intact islets of Langerhans in the mouse. *J. Physiol.* 517 (Pt 1), 85-93.
- Nadal, A., Roperio, A. B., Fuentes, E., Soria, B., & Ripoll, C. 2004. Estrogen and xenoestrogen actions on endocrine pancreas: from ion channel modulation to activation of nuclear function. *Steroids* 69, 531-536.

- Nadal, A., Ropero, A. B., Laribi, O., Maillet, M., Fuentes, E., & Soria, B. 2000. Nongenomic actions of estrogens and xenoestrogens by binding at a plasma membrane receptor unrelated to estrogen receptor alpha and estrogen receptor beta. *Proc. Natl. Acad. Sci. U.S.A.* 97, 11603-11608.
- Nadal, A., Rovira, J. M., Laribi, O., Leon-quinto, T., Andreu, E., Ripoll, C., & Soria, B. 1998. Rapid insulinotropic effect of 17beta-estradiol via a plasma membrane receptor. *FASEB J.* 12, 1341-1348.
- Newbold, R. R., Padilla-Banks, E., Jefferson, W. N., & Heindel, J. J. 2008. Effects of endocrine disruptors on obesity. *Int. J. Androl.* 31, 201-208.
- Orland, M. J., Chyn, R., & Permutt, M. A. 1985. Modulation of proinsulin messenger RNA after partial pancreatectomy in rats. Relationships to glucose homeostasis. *J. Clin. Invest.* 75, 2047-2055.
- Parsons, J. A., Brelje, T. C., & Sorenson, R. L. 1992. Adaptation of islets of Langerhans to pregnancy: increased islet cell proliferation and insulin secretion correlates with the onset of placental lactogen secretion. *Endocrinology* 130, 1459-1466.
- Penza, M., Montani, C., Romani, A., Vignolini, P., Pampaloni, B., Tanini, A., Brandi, M. L., Alonso-Magdalena, P., Nadal, A., Ottobri, L., Parolini, O., Bignotti, E., Calza, S., Maggi, A., Grigolato, P. G., & Di Lorenzo, D. 2006. Genistein affects adipose tissue deposition in a dose-dependent and gender-specific manner. *Endocrinology* 147, 5740-5751.
- Permutt, M. A. & Rotwein, P. 1983. Analysis of the insulin gene in noninsulin-dependent diabetes. *Am. J. Med.* 75, 1-7.
- Poitout, V., Hagman, D., Stein, R., Artner, I., Robertson, R. P., & Harmon, J. S. 2006. Regulation of the insulin gene by glucose and fatty acids. *J. Nutr.* 136, 873-876.
- Prado, C. L., Pugh-Bernard, A. E., Elghazi, L., Sosa-Pineda, B., & Sussel, L. 2004. Ghrelin cells replace insulin-producing beta cells in two mouse models of pancreas development. *Proc. Natl. Acad. Sci. U.S.A.* 101, 2924-2929.
- Prentki, M. & Nolan, C. J. 2006. Islet beta cell failure in type 2 diabetes. *J. Clin. Invest.* 116, 1802-1812.
- Ripoll, C., Martin, F., Manuel, R. J., Pintor, J., Miras-Portugal, M. T., & Soria, B. 1996. Diadenosine polyphosphates. A novel class of glucose-induced intracellular messengers in the pancreatic beta-cell. *Diabetes* 45, 1431-1434.
- Ripoll, C., Ropero, A. B., Alonso-Magdalena, P., Quesada, I., Fuentes, E., & Nadal, A. 2008. Rapid regulation of pancreatic alpha- and beta- cell signalling systems by estrogens. *Infect. Disord. Drug Targets.* 8, 61-64.
- Ropero, A. B., Alonso-Magdalena, P., Garcia-Garcia, E., Ripoll, C., Fuentes, E., & Nadal, A. 2008a. Bisphenol-A disruption of the endocrine pancreas and blood glucose homeostasis. *Int. J. Androl.* 31, 194-200.

- Ropero, A. B., Alonso-Magdalena, P., Quesada, I., & Nadal, A. 2008b. The role of estrogen receptors in the control of energy and glucose homeostasis. *Steroids* 73, 874-879.
- Rorsman, P., Eliasson, L., Renstrom, E., Gromada, J., Barg, S., & Gopel, S. 2000. The Cell Physiology of Biphasic Insulin Secretion. *News in Physiological Sciences* 15, 72-77.
- Rosen, E. D. & Spiegelman, B. M. 2006. Adipocytes as regulators of energy balance and glucose homeostasis. *Nature* 444, 847-853.
- Santos, R. M., Rosario, L. M., Nadal, A., Garcia-Sancho, J., Soria, B., & Valdeolmillos, M. 1991. Widespread synchronous $[Ca^{2+}]_i$ oscillations due to bursting electrical activity in single pancreatic islets. *Pflugers Archiv European Journal of Physiology* 418, 417-422.
- Sheeler, C. Q., Dudley, M. W., & Khan, S. A. 2000. Environmental estrogens induce transcriptionally active estrogen receptor dimers in yeast: activity potentiated by the coactivator RIP140. *Environ. Health. Perspect.* 108, 97-103.
- Shin, J. H., Hur, J. Y., Seo, H. S., Jeong, Y. A., Lee, J. K., Oh, M. J., Kim, T., Saw, H. S., & Kim, S. H. 2007. The ratio of estrogen receptor alpha to estrogen receptor beta in adipose tissue is associated with leptin production and obesity. *Steroids* 72, 592-599.
- Simoncini, T., Hafezi-Moghadam, A., Brazil, D. P., Ley, K., Chin, W. W., & Liao, J. K. 2000. Interaction of oestrogen receptor with the regulatory subunit of phosphatidylinositol-3-OH kinase. *Nature* 407, 538-541.
- Smith, E. P., Boyd, J., Frank, G. R., Takahashi, H., Cohen, R. M., Specker, B., Williams, T. C., Lubahn, D. B., & Korach, K. S. 1994. Estrogen resistance caused by a mutation in the estrogen-receptor gene in a man. *N. Engl. J. Med.* 331, 1056-1061.
- Sorenson, R. L., Brelje, T. C., & Roth, C. 1993. Effects of steroid and lactogenic hormones on islets of Langerhans: a new hypothesis for the role of pregnancy steroids in the adaptation of islets to pregnancy. *Endocrinology* 133, 2227-2234.
- Ueno, M., Carvalheira, J. B., Tambascia, R. C., Bezerra, R. M., Amaral, M. E., Carneiro, E. M., Folli, F., Franchini, K. G., & Saad, M. J. 2005. Regulation of insulin signalling by hyperinsulinaemia: role of IRS-1/2 serine phosphorylation and the mTOR/p70 S6K pathway. *Diabetologia* 48, 506-518.
- Valdeolmillos, M., Nadal, A., Contreras, D., & Soria, B. 1992. The relationship between glucose-induced K^+ ATP channel closure and the rise in $[Ca^{2+}]_i$ in single mouse pancreatic beta-cells. *J. Physiol.* 455, 173-186.
- Valdeolmillos, M., Santos, R. M., Contreras, D., Soria, B., & Rosario, L. M. 1989. Glucose-induced oscillations of intracellular Ca^{2+} concentration resembling bursting electrical activity in single mouse islets of Langerhans. *FEBS Lett.* 259, 19-23.

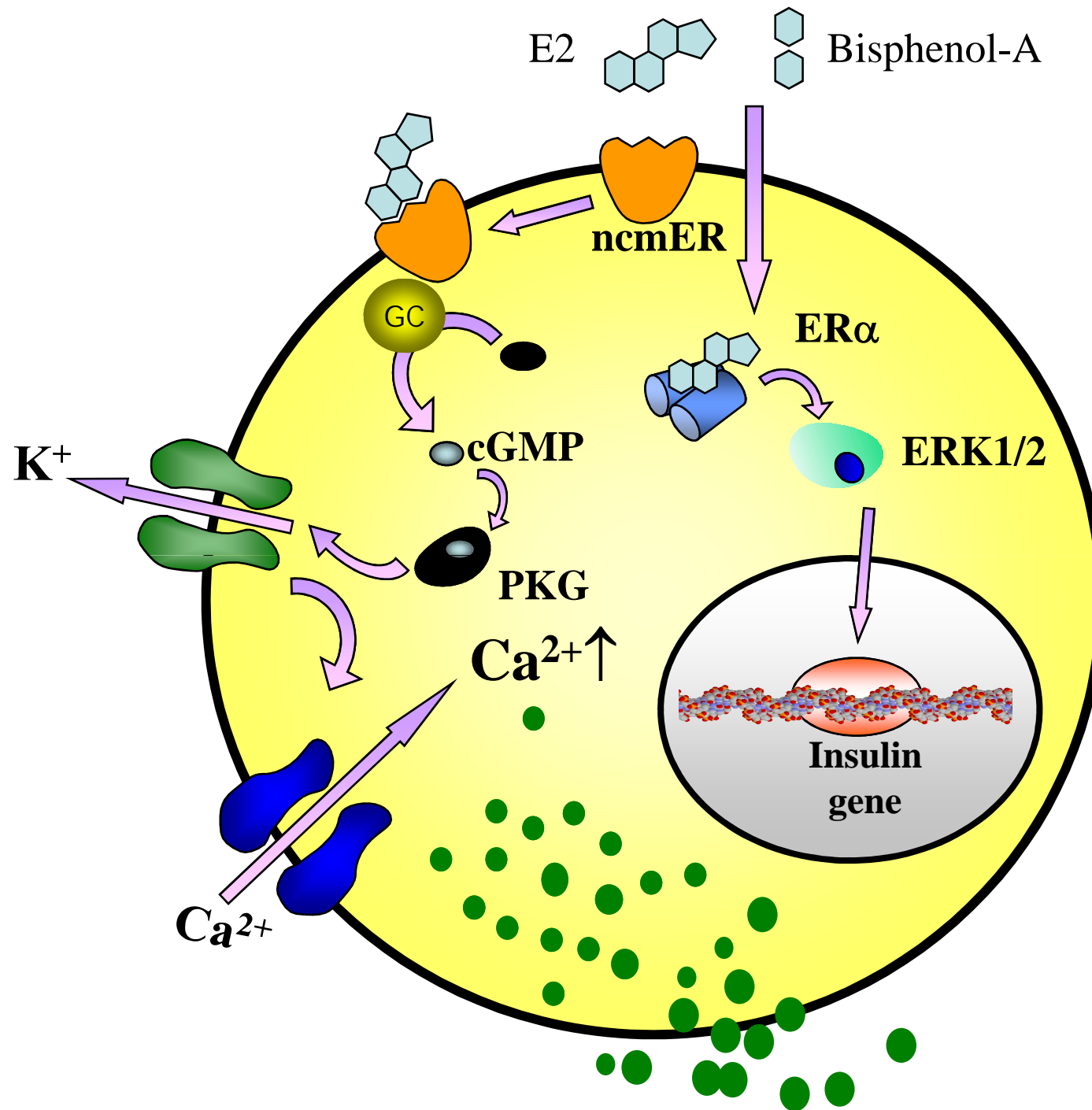
- Vital, P., Larrieta, E., & Hiriart, M. 2006. Sexual dimorphism in insulin sensitivity and susceptibility to develop diabetes in rats. *J. Endocrinol.* 190, 425-432.
- vom Saal, F. S. & Hughes, C. 2005. An extensive new literature concerning low-dose effects of bisphenol A shows the need for a new risk assessment. *Environ. Health Perspect.* 113, 926-933.
- vom Saal, F. S. & Myers, J. P. 2008. Bisphenol A and risk of metabolic disorders. *JAMA: The Journal of the American Medical Association* 300, 1353-1355.
- Wetherill, Y. B., Akingbemi, B. T., Kanno, J., McLachlan, J. A., Nadal, A., Sonnenschein, C., Watson, C. S., Zoeller, R. T., & Belcher, S. M. 2007. In vitro molecular mechanisms of bisphenol A action. *Reprod. Toxicol.* 24, 178-198.
- Zirilli, L., Rochira, V., Diazzi, C., Caffagni, G., & Carani, C. 2008. Human models of aromatase deficiency. *J. Steroid. Biochem. Mol. Biol.* 109, 212-218.

FIGURE LEGENDS

Figure 1. Proposed model for the action of 17 β -estradiol and bisphenol-A (BPA) in β -cells. In synergy with a stimulatory glucose concentration, binding of BPA or 17 β -estradiol to the ncmER activates a guanylyl cyclase (GC) and as a consequence a protein kinase G (PKG), whose action involves the closing of K_{ATP} channels. The subsequent depolarization opens L-type calcium channels; inducing Ca^{2+} influx and potentiating insulin release (see Nadal et al 2004 for a review). At the same time the activation of ER α by either E2 or BPA in the presence of stimulatory glucose levels rapidly activates ERK1/2 that regulates insulin gene expression through a still unknown pathway.

Figure 2. Action of excessive insulin signaling in different tissues. Human studies and the use of knock out mice reveal that the lack ER α produces insulin resistance and hyperinsulinemia. On the contrary, stimulation of ER α by E2 or BPA in the presence of glucose, overstimulates β -cells, inducing postprandial hyperinsulinemia, glucose intolerance and insulin resistance. We postulate that the hyperinsulinemia generated by the excess or the absence of ER α signaling, will produce dyslipidemia and obesity when affecting the liver and fat cells.

Figure



Figure

