Peroxisome proliferator-activated receptor γ, the ultimate liaison between fat and transcription

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The peroxisome proliferator-activated receptor gamma (PPARγ) is nuclear receptor that controls the expression of a large number of genes involved in adipocyte differentiation, lipid storage and insulin sensitization. PPARγ is bound and activated by fatty acid derivatives and prostaglandin J2. In addition, thiazolidinediones, non-steroidal anti-inflammatory drugs are synthetic ligands and agonists of this receptor. This review addresses the role of PPARγ in obesity and diabetes.

Adipogenesis: Adipose tissue: Gene expression: Fatty acids: Insulin resistance: Nuclear receptors: Thiazolidinediones: Type 2 diabetes: Transcription

Peroxisome proliferator-activated receptors (PPARs) compose a subfamily of the nuclear hormone receptor. Three distinct PPARs, termed α, δ (also called β, NUC-1 or FAAR) and γ, each encoded by a separate gene and showing a distinct tissue distribution pattern, have been described. Activated PPARs heterodimerize with another nuclear receptor, retinoid X receptor (RXR), and alter the transcription of numerous target genes after binding to specific response elements or PPREs. Since they are activated by various fatty acid metabolites as well as several drugs used in the treatment of metabolic disorders, PPARs translate nutritional, pharmacological and metabolic stimuli into changes in the expression of genes. In this review, we will focus our discussion on PPARγ, the most important PPAR species in adipose tissue. PPARγ plays crucial roles in adipogenesis and insulin sensitization and is activated by prostaglandin J2, certain fatty acid derivatives, thiazolidinedione anti-diabetic compounds, and a number of non-steroidal anti-inflammatory drugs. Recently, a number of additional functions were attributed to PPARγ, which suggested a more pleiotropic role affecting multiple fundamental pathways in the cell with wide ranging biomedical implications. In this review, we will focus on the metabolic functions of PPARγ. For more general information relating to the other PPARs and other aspects of PPARγ function, we refer to one of the several reviews on this topic for more exhaustive coverage (Desvergne & Wahli, 1994; Schoonjans et al. 1997).

PPARγ, a pivotal role in adipocyte differentiation and fatty acid metabolism

The molecular mechanisms that control adipocyte differentiation from adipose precursor cells (adipoblasts) are complex and are affected by numerous signaling pathways (for review see Fajas et al. 1998). It is currently thought that adipogenesis as well as the maintenance of the fully differentiated adipocyte phenotype requires an interplay between the PPARγ/RXR heterodimer and two other groups of transcription factors: the CCAATT enhancer binding proteins (C/EBP) and ADD-1/SREBP-1 (reviewed by Fajas et al. 1998). These transcription factors could also play a role in the pathology of adipose tissue such as seen in obesity or lipodystrophy.

Although all of these transcription factors can independently induce adipocyte differentiation in vitro, they act synergistically in vivo. During the initial phases of adipogenesis C/EBPβ and δ are induced in response to adipogenic hormones such as insulin or glucocorticoids (Wu et al. 1996). Both C/EBPs then induce the transcription of PPARγ2, via interaction with a C/EBP site in the PPARγ2 promoter (Fajas et al. 1997). PPARγ2 in its turn then induces the expression of PPARγ1 (Saladin et al. 1999). Another protein which is also induced during early adipocyte differentiation is the basic helix-loop-helix protein ADD-1/SREBP-1 (Kim & Spiegelman, 1996). This transcription factor, which plays a pivotal role in

Abbreviations: BMI, body mass index; C/EBP, CCAATT enhancer binding proteins; PPAR, peroxisome proliferator-activated receptor; RXR, retinoid X receptor; TNFα, tumor necrosis factor α; TZD, thiazolidinedione.

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cholesterol homeostasis, also regulates the expression of several genes in fatty acid metabolism, and hence it is suggested that ADD-1/SREBP-1 might control the generation of PPARγ ligands which in their turn enhance the transcriptional activity of PPARγ (Lopez et al. 1996; Shimano et al. 1996). Furthermore, our recent work showed that ADD-1/SREBP-1, as well as the related basic helix-loop-helix factor, SREBP-2, can induce PPARγ transcription through response elements in the PPARγ1 and γ3 promoters (Fajas et al. 1999). These interactions between cholesterol (ADD-1/SREBP) and fatty acid signaling (PPARγ) point to an interplay of these two lipids in adipocyte biology. Terminal adipocyte differentiation requires furthermore the concerted action of PPARα and fatty acid signaling.

Interestingly, obesity characterized by increased adipose tissue mass is associated with increased TNFα expression in adipose tissue. Although the exact role of high TNFα levels in obesity is unclear, it might constitute a regulatory mechanism to limit further increase in adipose tissue mass. This increase in TNFα levels in obesity also interferes with the insulin signaling pathways (Hotamisligil et al. 1995) contributing to the insulin resistance characteristic of the obese state (Hotamisligil et al. 1996).

**PPARγ, a role in insulin sensitivity and the determination of body mass**

Antidiabetic PPARγ agonists, such as thiazolidinediones (TZDs), improve insulin sensitivity in the muscle, an organ which PPARγ is hardly expressed (Fajas et al. 1997). Several hypotheses could explain this rather puzzling issue. One hypothesis is that the effects of thiazolidinediones are indirect (Shao & Lazar, 1997), and mediated by adipose tissue where PPARγ is mainly expressed. This effect could be exerted through two different processes. First, PPARγ activators may modulate the expression of adipocyte-derived signals affecting insulin sensitivity in muscle, such as TNFα (Hofmann et al. 1994) and leptin (Cohen et al. 1996; Liu et al. 1997). Second, PPARγ activation could induce a ‘fatty acid steal’ due to a specific TZD/PPARγ-mediated increase in lipid and fatty acid clearance by adipose tissue, without a concomitant increase in fatty acid delivery to the muscle (Martin et al. 1998). The ‘trapping’ of fatty acids in fat tissue would result in a decreased systemic availability and a diminished fatty acid uptake by the muscle, improving insulin sensitivity according to Randle (Randle et al. 1961). The antidiabetic effect of PPARγ agonists, agents that induce adipocyte differentiation, might seem illogical since obesity, the end-result of increased adipogenesis, is associated with insulin resistance. This discrepancy becomes apparent when one takes into account that on a whole body level, adipose tissue is absolutely required for glucose homeostasis in response to insulin. Indeed, human subjects (Moller & Flier, 1991) and transgenic animals with lipoatrophy (Moitra et al. 1998; Shimomura et al. 1998) are very insulin resistant. This indicates that storage of energy reserves in the adipocytes favors insulin sensitivity, and that the important adipogenic activity of PPARγ contributes to the insulin sensitization of TZDs. Other adipose-independent mechanisms however also contribute to the insulin-sensitizing effects of TZDs since these compounds retain this activity in transgenic mice that lack adipose tissue (Burant et al. 1997).

Another hypothesis to explain the action of TZDs is that it requires a direct effect on insulin sensitive tissues and that the minute quantities of PPARγ in muscle might be sufficient, or alternatively might be induced during TZD treatment, to lead to an eventual direct PPARγ-mediated response of the muscle. Potentially an enrichment of particular cofactors in muscle relative to other tissues could also contribute to a mechanism as such (reviewed in Gelman et al. 1999). Furthermore, in parallel to its action on adipose tissue, PPARγ activation might also affect insulin signaling more directly through the regulation of...
genes involved in glucose homeostasis. The mRNA encoding for the glucose transporter GLUT-4 (Wu et al. 1998) as well as the c-Cbl associated protein (Ribon et al. 1998) were recently reported to be induced by PPARγ. c-Cbl associated protein, which is only expressed in cells that are metabolically sensitive to insulin, is involved in insulin-stimulated tyrosine phosphorylation of c-Cbl (Ribon et al. 1998). It will await future studies to demonstrate whether the regulation of these genes, which are directly involved in insulin-mediated glucose homeostasis, is mediated via PPAR responsive elements in their promoters.

Twin and family studies suggest that close to 80 % of the variance in body mass index (BMI) is genetically determined (Bouchard & Perusse, 1993; Whitaker et al. 1997). Recently, mutations in PPARγ have been described (Beamer et al. 1998; Deeb et al. 1998; Ristow et al. 1998; Vigouroux et al. 1998; Yen et al. 1997). A rare Pro115Gln mutation in the NH2-terminal ligand-independent activation domain of PPARγ was found in four very obese subjects (Ristow et al. 1998). This mutation which results in a more active PPARγ led to increased adipocyte differentiation capacity in vitro (Ristow et al. 1998). We and others have recently described a much more common Pro12Ala substitution in the PPARγ2-specific exon B (Beamer et al. 1998; Deeb et al. 1998; Vigouroux et al. 1998; Yen et al. 1997). The PPARγ2 Ala allele, whose frequency ranges from approximately 0-12 among Caucasians to 0-02 in Japanese Americans (Deeb et al. 1998; Yen et al. 1997), was associated with a lower BMI, improved insulin sensitivity, and higher plasma HDL cholesterol levels (Deeb et al. 1998). The association with insulin sensitivity disappeared when corrected for BMI, indicating that the primary effect of this mutation was on body weight. The PPARγ Ala allele exhibited a reduced ability to transactivate responsive promoters. These results provide together with the observations made on the Pro115Gln substitution strong evidence of a role of PPARγ in the control of adipogenesis in vivo, such that a more active PPARγ (Pro115Gln) results in an increased BMI (Ristow et al. 1998), whereas the opposite is seen with a less active PPARγ (Pro12Ala) (Deeb et al. 1998). These observations appear at odds with two reports which found no association of the Pro12Ala substitution with insulin sensitivity (Beamer et al. 1998; Mori et al. 1998), and reported an association of the Ala allele with morbid obesity in Caucasians (Beamer et al. 1998), suggesting that the physiological consequences of the Pro12Ala polymorphism may be different in the lean and obese states. The recent observation that in Danish males, the Ala allele is associated with lower BMI among lean subjects and with higher BMI among obese subjects is consistent with this hypothesis (Ek et al. 1999), and indicate the importance of gene environment interactions in the determination of the phenotype.

The genetic and functional data on the Pro12Ala substitution point to the importance of the PPARγ2 specific B exon in determining the activity of PPARγ more particularly in adipocytes, the only tissue known to express significant amounts of PPARγ2. The function of the NH2-terminal residues of PPARγ2 is unknown. This domain may modulate nuclear import, ligand binding, DNA binding, or transcriptional activation by inducing a conformational change, or it may endow PPARγ2 with unique capacities to interact with co-activators or co-repressors that have been shown to interact with nuclear receptors. Support of the role of the NH2-terminus of PPARγ in transcriptional activity not only comes from the presence of a ligand-independent AF-1 domain in this part of the molecule (Werman et al. 1997) but also from its allosteric effects on ligand-dependent transcriptional activity through interdomain communication (Shao et al. 1998). The identification and characterization of proteins interacting with the NH2-terminus of PPARγ in the future will point to mechanisms by which this domain affects adipose tissue accumulation and metabolism.

**Conclusion**

Despite the fact that PPARγ is today a well characterized nuclear receptor, more detailed knowledge of its function in different specific tissues is indispensable to warrant chronic therapeutic use in metabolic disorders, such as insulin resistance and type 2 diabetes. Better understanding of PPARγ function will involve a thorough knowledge of its role in inflammation, cell cycle and cancer (reviewed in Gelman et al. 1999). This enhanced understanding of PPARγ will undoubtedly in the near future lead to an expansion of the therapeutic indication of PPARγ modulators, which will be based upon detailed characterization of the pleiotropic role of this receptor in different systems.

**References**


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