PGC-1 coactivators: Inducible regulators of energy metabolism in health and disease

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Members of the nuclear receptor (NR) superfamily relay physiologic and nutritional cues to critical gene regulatory responses. The molecular links between external stimuli, cellular signaling events, and NR-mediated transcriptional control are currently being unraveled. New information emerging over the past decade has demonstrated that NRs receive regulatory input through multiple mechanisms including levels of endogenous ligand, availability of heterodimeric NR partners, and posttranslational modifications. Activating signals trigger the recruitment of coactivator complexes onto the NR platform, leading to enzymatic modification of chromatin, increased access of the RNA polymerase II machinery to RNA, and activation of target gene transcription (Figure 1). Availability of certain coactivator proteins also serves critical regulatory functions linking physiologic stimuli to NR activity. Perhaps the best example of this latter mechanism involves the PPARγ coactivator-1 (PGC-1) family of transcriptional coactivators. PGC-1 coactivators serve as inducible NR “boosters” to equip the organism to meet the energy demands of diverse physiologic and dietary conditions. This Review will focus on the role of this interesting coactivator family in the control of organ-specific biologic responses to the physiologic and pathophysiologic milieu. Emphasis will be given to tissue-specific control of organ-specific biologic responses to the physiologic and nutritional cues to critical gene regulatory responses. A second activating complex, the thyroid hormone receptor–associated protein/vitamin D receptor–interacting protein (TRAP/DRIP, or Mediator) complex, docks on the carboxy terminal of PGC-1α (10). In addition, PGC-1α contains several domains within the carboxy-terminal region that couple pre-mRNA splicing with transcription (11).

Earlier studies involving forced overexpression of PGC-1α or PGC-1β in mammalian cells in culture demonstrated that these coactivators are sufficient to activate gene regulatory programs that drive increased capacity for cellular energy production (3, 5, 7, 12). PGC-1 coactivators effect biologic responses that equip the cell to meet the energy demands of a changing environment, including augmentation of mitochondrial biogenesis, cellular respiration rates, and energy substrate uptake and utilization. The PGC-1 coactivators exert these pleiotropic effects by directly coactivating a specific array of NR and non-NR transcription factors involved in the control of cellular metabolism. Following its discovery as a PPARα coactivator, Wu et al. demonstrated that PGC-1α coactivates nuclear respiratory factor-1 (NRF-1) and -2 (NRF-2) (5). NRFs regulate expression of mitochondrial transcription factor A (TFam), a nuclear-encoded transcription factor essential for replication, maintenance, and transcription of mitochondrial DNA (13–15). NRF-1 and NRF-2 also control the expression of nuclear genes encoding respiratory chain subunits and other proteins required for mitochondrial function (16, 17). These discoveries provided mechanistic insight into how PGC-1α activates the broad program of mitochondrial biogenesis and revealed that PGC-1 coactivators were capable of interacting with both NR and non-NR transcription factors.

Although PPARγ, NRF-1, and NRF-2 are key targets of PGC-1α–mediated coactivation, the diverse effects of this coactivator could not be explained by these interactions alone. Multiple PGC-1α partners have now been identified, indicating that this coactivator serves as a pleiotropic regulator of multiple pathways involved in cellular energy metabolism within and outside of the mitochondrion (Figure 2) (18, 19). Since the identification of PPARγ as a
PGC-1α transcription factor target, a variety of additional PGC-1 target NRs have been identified. This list includes PPARα (20), PPARβ (21), thyroid hormone receptor (1), retinoid receptors (1), glucocorticoid receptor (22), estrogen receptor (1, 22, 23), farnesyl X receptor (FXR) (24), pregnane X receptor (PXR) (25), hepatic nuclear factor-4 (HNF-4) (26), liver X receptor (LXR) (27), and the estrogen-related receptors (ERRs) (28, 29). In addition, several non-NR PGC-1 partners have been identified, including myocyte enhancer factor-2 (MEF-2) (30), forkhead box O1 (FOXO1) (31), SREBP1 (27), and Sry-related HMG box-9 (Sox9) (32). Through these transcription factor partners, PGC-1 exerts strong effects on many aspects of mitochondrial energy metabolism. For example, PGC-1α coactivates PPARα, a key regulator of genes involved in mitochondrial fatty acid oxidation (20). The PGC-1 target ERRα is an important regulator of mitochondrial energy transduction pathways including fatty acid oxidation and oxidative phosphorylation. In addition, ERRα is capable of cooperating with or directly activating the expression of NRF-1, NRF-2, and PPARα, defining an ERR “cross-regulatory circuit” that theoretically serves as an internal “amplifier” for the PGC-1α cascade (Figure 2). Finally, several of the PGC-1 coactivation targets regulate pathways outside of the mitochondrion — such as HNF-4 and FOXO1 (gluconeogenesis), MEF-2 (glucose transport), SREBP1 (lipogenesis), and Sox9 (chondrogenesis). In addition to serving a booster function, there is evidence that PGC-1 coactivators also confer target gene specificity. For example, selective activation of PPARα target genes encoding apo2, uncoupling protein-1, and glycerol kinase is dictated, in part, by the PGC-1α/PPARγ interaction on these promoters (1, 33). The mechanisms involved in the selection of specific targets by PGC-1α among tissues in a given physiologic context are an important area of investigation.

The discovery of PGC-1α as a cold-inducible coactivator prompted studies to determine whether its expression is regulated by developmental, physiologic, and dietary cues. One of the first clues that PGC-1α and PGC-1β serve diverse functions in multiple organ systems was the observation that they are expressed in broad, but tissue-enriched, patterns. PGC-1α and PGC-1β are highly expressed in mitochondria-enriched tissues with high energy demands, including BAT, heart, and slow-twitch skeletal muscle (1, 3, 4). PGC-1α is also enriched in brain and kidney. PGC-1α expression is induced in the heart after birth in parallel with a postnatal burst of mitochondrial biogenesis and a shift toward reliance on mitochondrial fatty acid oxidation as the major source of ATP production (12). The PGC1A gene is highly inducible in response to physiologic conditions that demand increased mitochondrial energy production. For example, PGC-1α expression is stimulated by exercise in skeletal muscle (34–38) and by fasting in the heart and liver (12, 26). Interestingly, PGC-1β expression is also induced by fasting, but not cold exposure, indicating that factor-specific upstream regulatory circuits exist (3, 39).

As would be predicted by its inducibility, the expression and activity of PGC-1α are linked to a variety of upstream signaling pathways (Figure 2). In BAT and liver (and likely other tissues), the β-adrenergic/cAMP pathway activates PGC1A gene transcription (1). Calcineurin A and calcium/calmodulin–dependent protein kinase (CaMK) activate PGC-1α expression in striated muscle (40–42). The AMP-activated protein kinase (AMPK) has also been implicated in the control of muscle PGC-1α expression (43). p38 MAPK has been shown to activate PGC-1α by releasing p160-mediated repression and by increasing PGC-1α protein stability (44–46). More recently, NO was shown to activate mitochondrial biogenesis coincident with increased PGC-1α expression in a variety of cell types, including adipocytes and HeLa cells (47). Given the known role of NO as a vasodilator, it is tempting to speculate that this key upstream regulatory pathway coordinate regulates downstream events including an increase in the capacity to utilize oxygen in mitochondria. In addition to phosphorylation, other posttranslational modifications, including acetylation, arginine methylation, and interaction with repressor proteins (e.g., p160), modulate PGC-1α activity (45, 48, 49).

The transcriptional regulatory factors that link upstream signaling pathways to PGC1A gene expression are being delineated.
The calcineurin A–mediated activation of the PGC1A promoter is dependent on MEF-2 response elements, whereas CaMK-mediated regulation requires CREB-binding sites (40–42). The transcription factor CREB activates PGC1A gene transcription in hepatocytes, implicating this factor in the PGC-1α–mediated control of gluconeogenesis (50). The forkhead transcription factor FOXO1 activates the human PGC1A promoter in a hepatoma cell line (51), an effect that is suppressed by protein kinase B/Akt signaling, suggesting a mechanism for negative regulation of PGC-1α expression by insulin in the liver.

Given that PGC-1α integrates regulatory input from a variety of upstream regulatory pathways among multiple tissues, in vivo studies have been necessary to define the bona fide biologic functions downstream of this powerful transcriptional coactivator. In vivo studies have been enabled by the development of generalized and conditional transgenic PGC-1α gain-of-function mouse models. In addition, 2 independent generalized PGC-1α–deficient mouse lines (Pgc1a−/− mice) have been generated using gene targeting strategies (52, 53). Both lines are viable and exhibit multisystem energy metabolic abnormalities that were unveiled by physiologic or nutritional stressors.

PGC-1 signaling and the heart

The extraordinary energy demands of the heart are met by a high-capacity mitochondrial system. Accordingly, it is not surprising that PGC-1α and PGC-1β are highly expressed in this organ (1, 3, 54). Although the exact roles of PGC-1β and PRC in heart have not been defined, several lines of evidence indicate that PGC-1α controls cardiac energy metabolic pathways during development and in response to physiologic stressors. First, cardiac PGC-1α expression is induced after birth as the heart turns toward mitochondrial fatty acid oxidation as the chief energy source (12). PGC-1α expression is also activated in the heart by fasting (12), a physiologic stimulus that markedly increases the reliance of the heart on mitochondrial fat oxidation for ATP production. Second, PGC-1α coactivates PPARα and ERRα, NRs that control genes involved in cardiac fatty acid oxidation and mitochondrial respiratory function (55). Third, forced overexpression of PGC-1α in cardiac myocytes in culture activates mitochondrial biogenesis (12). Interestingly, in contrast to the BAT, where PGC-1α drives uncoupled respiration, PGC-1α overexpression drives coupled respiration in the cardiac myocyte (12).

Gain-of-function studies in transgenic mice have demonstrated potential biologic functions of PGC-1α in the heart in vivo. Two

Figure 2
The PGC-1 gene regulatory cascade. The schematic indicates the upstream signaling events and downstream gene regulatory actions of the inducible PGC-1 coactivators, using PGC-1α as the representative factor. The interaction of PGC-1α with its cognate transcription factor targets is shown linked to specific organ systems. For example, PGC-1α coactivates members of the PPAR nuclear receptor transcription factor family, to activate the expression of genes involved in mitochondrial fatty acid oxidation. The signaling pathways shown at the top of each organ system transduce extracellular physiologic and nutritional stimuli to the expression and/or activity of PGC-1α. LXR, liver X receptor; TAG, triacylglycerol; RXR, retinoid X receptor; mtDNA, mitochondrial DNA; OXPHOS, oxidative phosphorylation.
transgenic mouse models with cardiac-restricted overexpression of PGC-1α have been developed. In the first model, mice with constitutive, postnatal cardiac overexpression of PGC-1α under control of the cardiac α-myosin heavy chain promoter (MHC–PGC-1α mice) were generated (12). The hearts of MHC–PGC-1α mice exhibit marked activation of cardiac myocyte mitochondrial biogenesis, leading, ultimately, to death from heart failure (12). Subsequently, a bitransgenic, tissue-specific, tetracycline-inducible PGC-1α mouse was established (the cs-tet-on PGC-1α mouse) (56). Studies of cs-tet-on PGC-1α mice revealed developmental stage-specific effects of PGC-1α. Overexpression of PGC-1α in neonatal heart triggers dramatic expansion of mitochondria within the cardiac myocytes. In contrast, acute cardiac overexpression of PGC-1α in adult mice results in a modest mitochondrial biogenic response and, after several weeks, cardiomyopathy associated with mitochondrial ultrastructural abnormalities. The basis for cardiomyopathy following PGC-1α activation is unknown but likely involves dysregulated mitochondrial metabolism.

Recent loss-of-function studies further support a role for PGC-1α in the control of myocardial metabolism and function. Interestingly, the severity of the cardiac phenotype varies between the 2 independently generated lines of PGC-1β-deficient mice. Both lines demonstrate that PGC-1α is not essential for the fundamental process of mitochondrial biogenesis in the heart; myocardial mitochondrial volume density is not significantly altered in either Pgc1α−/− line (53, 57). The PGC-1α-deficient mice produced by the Spiegelman group exhibit moderate, age-related base-line cardiac dysfunction as determined by echocardiography (57). Hearts isolated from this line of mice also exhibit a modest impairment in maintenance of ATP and phosphocreatine homeostasis in response to the β-adrenergic agonist dobutamine as determined by NMR spectroscopy. These metabolic abnormalities are associated with diminished expression of genes involved in mitochondrial fatty acid oxidation, the TCA cycle, and oxidative phosphorylation. In contrast, the PGC-1α-deficient mice produced by Leone et al. do not exhibit overt dysfunction by echocardiography under basal conditions; however, this second line of Pgc1α−/− mice exhibit a blunted heart rate response to exercise and β-adrenergic stimulation (53). The mechanistic basis for the dissimilarities between the 2 lines of Pgc1α−/− mice is unclear. It is possible that epigenetic effects due to differences in strain background or gene targeting strategies account for the divergent phenotypes.

Several lines of recent evidence implicate PGC-1α in the pathogenesis of heart failure. First, in mouse models of chronic pressure overload such as occurs in long-standing hypertension, PGC-1α levels are downregulated along with the expression of PPARGC1α target genes involved in mitochondrial fatty acid oxidation (58–60). Second, transcriptional profiling revealed downregulation of PGC-1α gene expression in the failing hearts of transgenic mice in which cyclin T/Cdk9, an RNA polymerase kinase, is overexpressed in the heart (61, 62). Forced expression of PGC-1α in the mutant cardiac myocytes prevented the apoptotic phenotype (62). These results are interesting given that mitochondrial respiratory function and high-energy phosphate stores are known to be reduced in end-stage heart failure (63). Lastly, chronic overexpression of PGC-1α in heart leads to a cardiomyopathic phenotype (12, 56). Thus, emerging evidence links altered PGC-1α activity to cardiac dysfunction. However, whether PGC-1α plays an etiologic role in the pathogenesis of heart failure remains to be determined.

PGC-1 signaling and skeletal muscle
The expression of PGC-1α is enriched in skeletal muscle, particularly in oxidative fiber types. Studies in rodent models indicate that both short-term exercise and endurance training activate PGC-1α expression in skeletal muscle (34, 35, 64, 65). Subsequent studies in humans have further demonstrated remarkable inducibility of PGC-1α in response to acute bouts of exercise or endurance training (38, 66) and have indicated that PGC-1α levels are increased mainly in type IIa fibers after endurance training (66). Although the upstream signaling events involved in the activation of PGC-1α expression in exercising muscle are not well defined, several pathways have been implicated. The calcineurin A and CaMK pathways are linked to muscle PGC1A gene transcription through MEF-2 factors (40–42). Recently, the p38 MAPK and AMPK pathways have also been implicated in the control of PGC-1α expression in skeletal muscle after exercise training (43, 67).

The biologic roles of PGC-1α in skeletal muscle have been elucidated largely through murine gain-of-function and loss-of-function studies. Lin et al. developed mice with skeletal muscle–specific overexpression of PGC-1α driven by the muscle creatine kinase (MCK) promoter (68). Forced expression of PGC-1α at high physiologic levels in the MCK transgenic mice resulted in an increased proportion of oxidative or type I muscle fibers coincident with an increase in the expression of mitochondrial markers. This fiber type transition was also manifest by red muscle coloration, increased expression of contractile protein characteristic of type I fibers, and resistance to electrically stimulated fatigue (68). These results indicated that PGC-1α is sufficient to drive the slow-twitch skeletal muscle program. Complementary loss-of-function studies demonstrated that Pgc1α−/− mice exhibit diminished mitochondrial number and respiratory capacity in slow-twitch skeletal muscle (53). In contrast, measures of mitochondrial function and density are normal in fast-twitch fibers of the PGC-1α-deficient mice. However, exercise capacity, as measured on a motorized treadmill, and fatigue resistance index in electrically stimulated muscle, are significantly reduced in the Pgc1α−/− mice (53). Taken together, these results strongly implicate PGC-1α signaling as a key mediator of the energy metabolic and structural adaptation of muscle to exercise.

Recent evidence also implicates PGC-1α in the regulation of muscle glucose metabolism. The first clue came from studies demonstrating that PGC-1α robustly activates expression of glucose transporter 4 (GLUT4) in skeletal muscle cells in culture by coactivating MEF-2c (30). More recently, PGC-1α was found to repress glucose oxidation in muscle cell lines by activating the expression of the gene encoding pyruvate dehydrogenase kinase 4 via its NR partner, ERRα (69). These latter results suggest that PGC-1α controls muscle fuel selection by increasing fatty acid oxidation while temporarily shutting down glucose oxidation—a gene regulatory equivalent of the fatty acid–glucose cycle. Inhibition of glucose oxidation combined with increased muscle glucose uptake could serve to replenish muscle glycogen stores to prepare for the next bout of exercise.

PGC-1 signaling and hepatic function
Under normal, ad libitum–fed conditions, the expression of PGC-1α and PGC-1β is relatively low in liver compared with other tissues that rely on aerobic metabolism for ATP production (1, 39). However, hepatic PGC1A and PGC1B gene expression is robustly induced by fasting (39, 50, 70). During short-term star-
PGC-1α participates directly in the regulation of energy metabolic pathways but also influences insulin sensitivity, glucose tolerance, and hepatic triglyceride production and secretion, resulting in circulating hypertriglyceridemia and hypercholesterolemia. Conversely, it was previously shown that activation of PGC-1α in liver diminished triglyceride production and secretion (24). The mechanistic explanation for these surprising results came from gene regulatory studies demonstrating that PGC-1β, but not PGC-1α, activates the expression of genes involved in lipogenesis and triglyceride secretion via direct coactivation of SREBP1c (27), a transcription factor that plays a critical role in the control of lipogenesis. The region of PGC-1β that mediates the protein-protein interaction with SREBP is not conserved among PGC-1 family members; this provides an explanation for the observed isoform selectivity. This work provides a potential mechanistic basis for the known association between diets high in saturated or trans-fat and hyperlipidemia.

In sum, evidence is mounting that induction of PGC-1α and PGC-1β expression in liver is a critical regulatory event leading to the activation of energy metabolic pathways that serve to increase ATP production and exert homeostatic control, especially in the context of fasting. Given the importance of hepatic lipid metabolic derangements in common diseases such as nonalcoholic steatotic hepatitis and alcoholic liver disease, as well as the link between liver insulin resistance and diabetes, the PGC-1 regulatory circuits represent potential new therapeutic targets for hepatic disease states.

Paradoxical roles for PGC-1α in insulin resistance and diabetes mellitus
Recent studies in animal models and in humans link altered PGC-1α signaling to glucose intolerance, insulin resistance, and diabetes. However, the role of PGC-1α as a protective factor versus mediator of disease progression is unclear, particularly given that its predicted effects on insulin sensitivity and glucose tolerance vary across tissues (Figure 3). Associations between PGC-1α and diabetes have been identified in studies of human genetic variants. A common polymorphism in the coding region of the PGCIA gene (Gly482Ser) and a specific promoter haplotype are associated with...
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an increased risk of type 2 diabetes (74–81). However, other studies have not found this association (82, 83). Additionally, the target tissues affected and whether these polymorphisms result in increased or decreased PGC-1α activity remain unclear.

PGC-1α activity is robustly activated in diabetic liver as it is in the fasted state (26, 31, 50, 70), potentially increasing hepatic glucose production that contributes to circulating hyperglycemia. Moreover, PGC-1α may promote insulin resistance directly by inducing TRB-3, an inhibitor of Akt signaling, a critical downstream component of the insulin signaling pathway (71). The precise mechanisms involved in the regulatory cross-talk between insulin signaling and PGC-1α activity in the diabetic state represent an area of active research.

In the pancreatic β cell, rates of mitochondrial ATP synthesis are inexorably coupled to insulin secretion by ATP-sensing K+ channels, which control insulin release. PGC-1α is also activated in the β cell in several rodent models of obesity and type 2 diabetes (84), and PGC-1α overexpression suppressed glucose-stimulated membrane depolarization and insulin secretion in cultured islets or insulinoma cell lines (84). Moreover, whereas transplantation of normal islets into mice rendered diabetic by streptozotocin returned blood glucose levels to normal, PGC-1α-overexpressing islets were unable to reverse experimentally induced diabetes. The β cell phenotype of the PGC-1α-deficient mice and the effects of other PGC-1 family members in the β cell have not yet been delineated.

In contrast to results in liver and the β cell, the bulk of evidence focused on skeletal muscle suggests that PGC-1α may be protective from the development of insulin resistance. First, as described above, PGC-1α activates expression of GLUT4 (30). Second, PGC-1β overexpression in skeletal muscle protects mice from high-fat diet-induced obesity and insulin resistance (6). Third, inherited mitochondrial deficiencies are linked with the development of systemic metabolic defects and diabetes (85). Accordingly, PGC-1α, a critical booster of mitochondrial function, is an excellent candidate for preventing insulin resistance secondary to mitochondrial dysfunction. Fourth, a series of recent studies in humans have shown an interesting inverse correlation between muscle PGC-1α levels and mitochondrial activity with insulin resistance and diabetes (86–88). However, a separate recent study did not find a correlation between muscle mitochondrial derangements and PGC-1α levels in insulin-resistant humans (89). Given that the published results focused on PGC-1α levels in insulin-resistant muscle are largely correlative, the role of alterations in PGC-1α activity as etiologic versus a secondary phenomenon remains unclear.

One approach to unraveling the paradoxical, tissue-specific actions of PGC-1α on systemic glucose metabolism and insulin sensitivity is through studies of recently developed genetically modified mouse models. Systemic glucose tolerance and insulin sensitivity have been characterized in both PGC-1α-deficient lines. Although some differences exist in the 2 lines, the results indicate that both Pgc1a−/− lines are modestly protected against insulin resistance caused by high-fat diet. Interestingly, this insulin-sensitive phenotype occurs despite reduced respiratory capacity of mitochondria in the skeletal muscle of the mice (53). It is possible that reduced hepatic glucose production via the gluconeogenic pathway contributes to the enhanced glucose tolerance of PGC-1α-deficient mice (Figure 3). Indeed, as described above, liver-specific overexpression and knockdown strategies indicate that PGC-1α, when activated, drives hepatic glucose production, a potential contributor to the development of obesity-related diabetes. In addition, one of the PGC-1α-deficient lines exhibited increased activity and partial resistance to weight gain, which could contribute to the phenotype (52). Given the mounting evidence of a link between diabetes and PGC-1α activity, this represents an important focus for future investigation.

PGC-1 coactivators: the future

A recent explosion of new information indicates that the PGC-1 family of coactivators serves key functions in the dynamic transcriptional control of energy metabolic pathways in a variety of mammalian tissues. The importance of PGC-1α and PGC-1β as boosters of NR function has provided exciting new avenues for understanding the fundamental connections between alterations in the external environment and adaptive metabolic responses of striated muscle and liver. Moreover, evidence is mounting that dysregulation of the PGC-1α regulatory axis contributes to the pathogenesis of common disease states including diabetes and heart failure. However, the role of these powerful and highly inducible coactivators as protectors versus mediators of disease has not been well defined and will require additional translational studies bridging animal models, such as conditional genetically modified mouse models, and humans. Given the versatile and pleiotropic nature of the PGC-1 family regulatory circuit, it is envisioned that, after the elucidation of the precise roles of these coactivators in disease states, specific PGC-1/NR regulatory limbs could prove to be exciting new therapeutic targets.

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