



# Transcriptional control of mitochondrial biogenesis: the central role of PGC-1 $\alpha$

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Although the concept of energy starvation in the failing heart was proposed decades ago, still very little is known about the origin of energetic failure. Recent advances in molecular biology have started to elucidate the transcriptional events governing mitochondrial biogenesis. In particular, a great step was taken with the discovery that peroxisome proliferator-activated receptor gamma co-activator (PGC-1 $\alpha$ ) is the master regulator of mitochondrial biogenesis. The molecular mechanisms underlying the downregulation of PGC-1 $\alpha$  and the consequent decrease in mitochondrial function in heart failure are, however, still poorly understood. Indeed, the main pathways involved in mitochondrial biogenesis are thought to be up- rather than down-regulated in pathological hypertrophy and heart failure. The current review summarizes recent advances in this field and is restricted to the heart when cardiac data are available.

## 1. Mitochondrial biogenesis

### 1.1 Definition

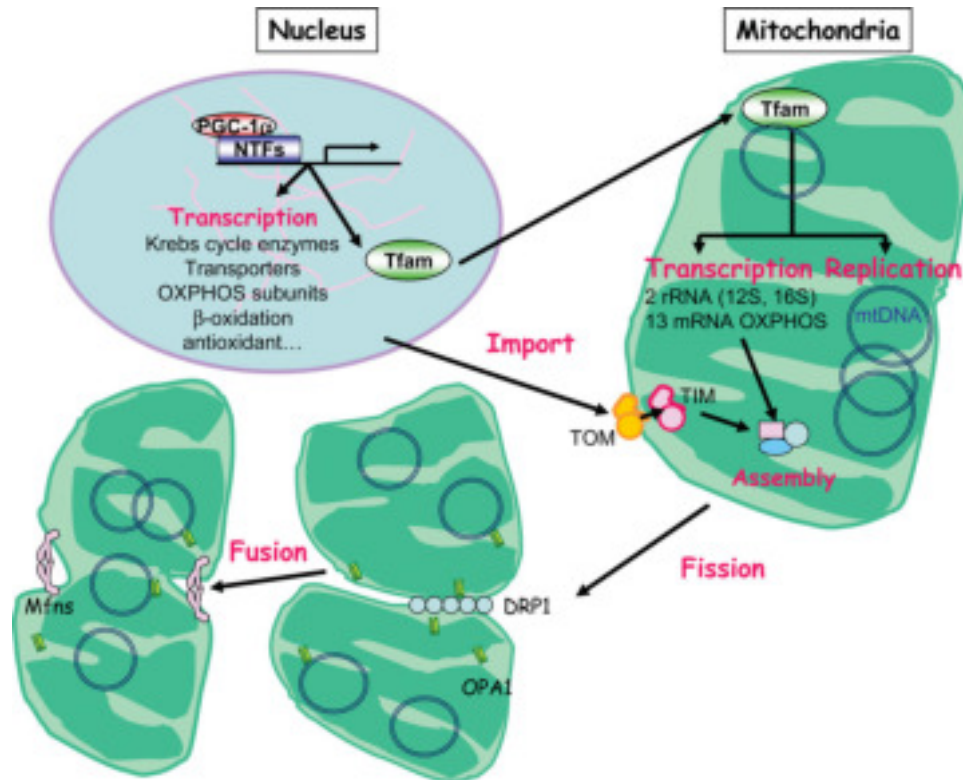
Mitochondrial biogenesis can be defined as the growth and division of pre-existing mitochondria. According to the well-accepted endosymbiotic theory, mitochondria are the direct descendants of an  $\alpha$ -proteobacteria endosymbiont that became established in a host cell. Due to their ancient bacterial origin, mitochondria have their own genome and a capacity for autoreplication. Mitochondrial proteins are encoded by the nuclear and the mitochondrial genomes. The double-strand circular mitochondrial DNA (mtDNA) is  $\sim$ 16.5 kb in vertebrates and contains 37 genes encoding 13 subunits of the electron transport chain (ETC) complexes I, III, IV, and V, 22 transfer RNAs, and 2 ribosomal RNAs necessary for the translation. Correct mitochondrial biogenesis relies on the spatiotemporally coordinated synthesis and import of  $\approx$ 1000 proteins encoded by the nuclear genome, of which some are assembled with proteins encoded by mitochondrial DNA within newly synthesized phospholipid membranes of the inner and outer mitochondrial membranes. In addition, mitochondrial DNA replication and mitochondrial fusion and fission mechanisms must also be coordinated (Figure 1). All of these processes have to be tightly regulated in order to meet the tissue requirements. Mitochondrial biogenesis is triggered by environmental

stresses such as exercise, cold exposure, caloric restriction and oxidative stress, cell division and renewal, and differentiation. The biogenesis of mitochondria is accompanied by variations in mitochondrial size, number, and mass. The discovery that alterations in mitochondrial biogenesis contribute to cardiac pathologies such as the hypertrophied or failing heart have increased the interest of the scientific community in this process and its regulation.

### 1.2 Protein import

Because the majority of mitochondrial proteins are encoded in the nucleus, a mechanism for the targeting, import, and correct assembly exists to ensure proper mitochondrial function and shape (for review see reference<sup>1,2</sup>). Following activation of the nuclear genome, mRNAs are translated in the cytosol to precursor proteins having signals for targeting to specific mitochondrial compartments. These proteins are escorted by molecular chaperones, unfolded, and imported into mitochondria via the translocase of the outer membrane complex (TOM). After transfer across the outer membrane, certain precursors are directed through the import machinery of the inner membrane complex (TIM) into the mitochondrial matrix in a membrane potential-dependent manner. Subsequently, these precursors are cleaved of their import sequences and are refolded by intramitochondrial proteins. A majority of mitochondrial protein precursors, however, do not contain typical N-terminal targeting signals but instead contain targeting information within

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**Figure 1** Schematic representation of mitochondrial biogenesis. Peroxisome proliferator-activated receptor gamma co-activator (PGC-1 $\alpha$ ) activates nuclear transcription factors (NTFs) leading to transcription of nuclear- encoded proteins and of the mitochondrial transcription factor Tfam. Tfam activates transcription and replication of the mitochondrial genome. Nuclear-encoded proteins are imported into mitochondria through the outer- (TOM) or inner (TIM) membrane transport machinery. Nuclear- and mitochondria-encoded subunits of the respiratory chain are then assembled. Mitochondrial fission through the dynamin-related protein 1 (DRP1) for the outer membrane and OPA1 for the inner membrane of mitochondria allow mitochondrial division while mitofusins (Mfn) control mitochondrial fusion. Processes of fusion/fission lead to proper organization of the mitochondrial network. OXPHOS: oxidative phosphorylation.

their mature sequences. Other mechanisms ensure proper assembly and processing of the different subunits in the mitochondrial complexes of the respiratory chain at the inner membrane or in the matrix. These processes are an integral part of mitochondrial biogenesis.

### 1.3 Fusion and fission

Mitochondria in the cells of most tissues are tubular, and dynamic changes in morphology are driven by fission, fusion, and translocation.<sup>3</sup> The ability to undergo fission/fusion enables mitochondria to divide and helps ensure proper organization of the mitochondrial network during biogenesis. The processes of fission/fusion are controlled by GTPases, most of which were identified in genetic screens in yeast (for recent reviews see reference<sup>4,5</sup>). Mitochondrial fission is driven by dynamin-related proteins (DRP1 and OPA1), while mitochondrial fusion is controlled by mitofusins (Mfn1 and 2). Mitofusins are highly expressed in heart and skeletal muscle, and their expression is induced during myogenesis and physical exercise.<sup>6,7</sup> In addition to the control of the mitochondrial network, Mfn2 also stimulates the mitochondrial oxidation of substrates, cell respiration, and mitochondrial membrane potential, suggesting that this protein may play an important role in mitochondrial metabolism, and as a consequence, in energy balance.<sup>6</sup> OPA1, by contrast, is involved in the remodelling of cristae. Mfn and DRP1 expression increases in parallel with mitochondrial content and exercise capacity in human

skeletal muscle,<sup>8</sup> suggesting that fusion/fission processes are an integral part of mitochondrial biogenesis. However, these processes have received less attention in the heart up until now.

### 1.4 Cardiolipin biosynthesis

Increases in mitochondrial content/number involve the proliferation of mitochondrial membranes. Phospholipids are important structural and functional components of mitochondrial membranes,<sup>9</sup> and are involved in the regulation of various processes including apoptosis, electron transport, and mitochondrial lipid and protein import. Cardiolipin is the main functional phospholipid of the mitochondrial inner membrane, representing 8–15% of the entire cardiac phospholipid mass, and is the only phospholipid that is both synthesized and localized exclusively within mitochondria. Cardiolipin plays a key role in the activity of several inner membrane proteins and in the binding of mitochondrial creatine kinase in the vicinity of translocase. *De novo* synthesis of cardiolipin starts with the conversion of phosphatidic acid to CDP-diacylglycerol and ends with the condensation of phosphatidylglycerol and CDP-diacylglycerol by cardiolipin synthase. A second mechanism of cardiolipin biosynthesis is through a deacylation–reacylation reaction catalysed by phospholipases and acyltransferases, which are regarded as the principal enzymes involved in phospholipid remodelling in mammalian tissues.<sup>9</sup>

## 2. Transcriptional control of mitochondrial biogenesis

Much progress in uncovering the transcriptional regulatory mechanisms involved in mitochondrial biogenesis has been made in the last 10 years. Some of the major research will be presented here. Readers are referred to recent excellent reviews on the subject for more complete details.<sup>10–13</sup>

### 2.1 Mitochondrial transcription factor A

Transcription and replication of mitochondrial DNA is driven by the nuclear-encoded mitochondrial transcription factor A (Tfam), which binds to a common upstream enhancer of the promoter sites of the two mitochondrial DNA strands. Cardiac-specific Tfam deletion results in decreased levels of mtDNA, impaired respiratory chain function, cardiac hypertrophy, and progressive cardiomyopathy.<sup>14</sup> Additionally, two proteins that interact with the mammalian mitochondrial RNA polymerase and Tfam, TFB1M and TFB2M, can support promoter-specific mtDNA transcription.<sup>15</sup> Although usually complex and promoter-specific, certain DNA binding motifs are present in the promoters of several of genes encoding oxidative phosphorylation (OXPHOS) complex subunits and enzymes involved in mtDNA metabolism and are, therefore, able to participate in a coordinated response. These motifs include the OXBOX/REBOX motif, the Mt motif, Sp1, and nuclear respiratory factor (NRF) motifs (see Garesse and Vallejo<sup>11</sup> for original references).

### 2.2 Nuclear respiratory factors

The nuclear respiratory factors 1 and 2 have been linked to the transcriptional control of many mitochondrial genes whose list has expanded greatly in the last few years (see Table 1 in Kelly and Scarpulla<sup>10</sup>). Electrical stimulation of neonatal cardiomyocytes produces an increase in mitochondrial content that is preceded by enhanced expression of NRF1, indicating a role for this transcription factor in cardiac mitochondrial biogenesis.<sup>16</sup> The Tfam promoter contains recognition sites for NRF1 and/or NRF2, thus allowing coordination between mitochondrial and nuclear activation during mitochondrial biogenesis. However, a subset of genes does not appear to be regulated by NRFs. For example, fatty acid transport proteins and oxidation enzyme genes are mainly regulated by the peroxisome proliferator-activated receptor alpha PPAR $\alpha$  (see below and Finck and Kelly<sup>12</sup> for recent review).

### 2.3 Peroxisome proliferator-activated receptor gamma co-activator

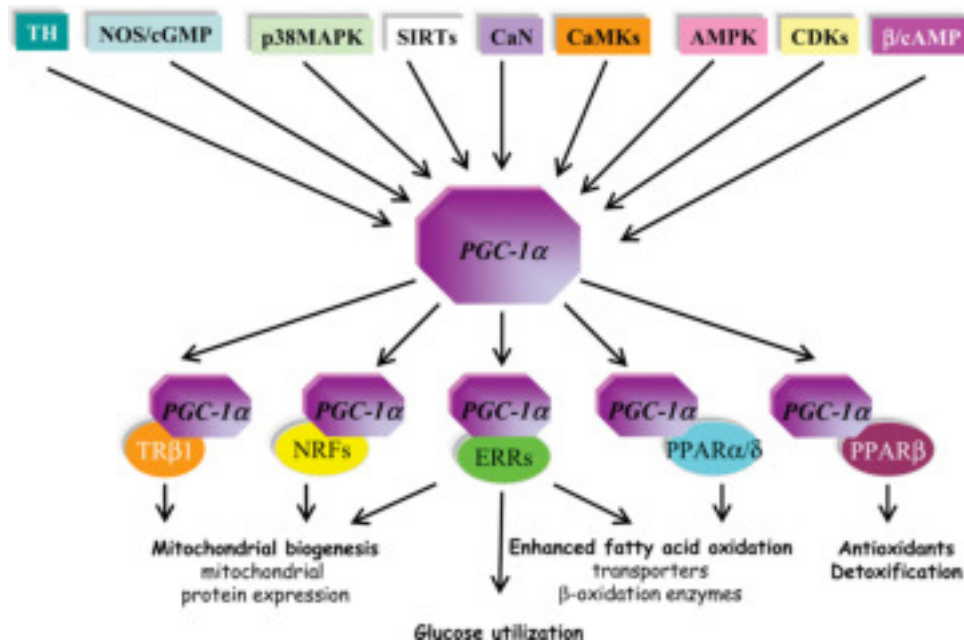
Since its discovery by Spiegelman and coworkers,<sup>17</sup> peroxisome proliferator-activated receptor gamma co-activator (PGC-1 $\alpha$ ) has been the focus of much attention. PGC-1 $\alpha$  lacks DNA-binding activity but interacts with and co-activates numerous transcription factors including NRFs on the promoter of mtTFA.<sup>17</sup> Mitochondrial biogenesis and respiration are stimulated by PGC-1 $\alpha$  through powerful induction of NRF1 and NRF2 gene expression. PGC-1 $\alpha$  is enriched in tissue with high oxidative activity-like heart and brown adipose tissue and, to a lesser extent, skeletal muscle, and kidney, and it is rapidly induced under conditions of increased energy

demand such as cold, exercise, and fasting. Data are accumulating which show PGC-1 $\alpha$  to be a master regulator of mitochondrial biogenesis in mammals. Ectopic expression of PGC-1 $\alpha$  in myotubes strongly induces the expression of downstream transcription factors such as NRFs and Tfam.<sup>17</sup> Unlike NRFs or Tfam, however, PGC-1 $\alpha$  levels correlate with cardiac and skeletal muscle oxidative capacity, suggesting that it plays a major role in setting mitochondrial content.<sup>18</sup> PGC-1 $\alpha$  expression is greatly enhanced in the developing mouse heart immediately before the burst of mitochondrial biogenesis that precedes birth.<sup>19</sup> Constitutive cardiac-specific PGC-1 $\alpha$  overexpression in mice results in uncontrolled mitochondrial proliferation, leading to dilated cardiomyopathy.<sup>19</sup> During the neonatal stages, inducible cardiac-specific overexpression of PGC-1 $\alpha$  leads to a dramatic increase in mitochondrial number and size, concomitant with upregulation of genes associated with mitochondrial biogenesis.<sup>20</sup> In the adult, this leads to a more modest increase in mitochondrial number, but with perturbation of mitochondrial ultrastructure and development of cardiomyopathy.<sup>20</sup> Given the significant volume occupied by mitochondria in mouse cardiomyocyte (~45% in adult), and the extremely low cytosolic volume (around 4–7%), any increase in mitochondrial mass will automatically be at the expense of myofibrillar volume, thus compromising contractile function. Consequently, it is likely that a strict control of mitochondrial volume exists in the adult heart in order to keep constant the ratio of mitochondrial to myofibrillar volume. Two lines of PGC-1 $\alpha$ -deficient mice have been independently generated, which differ slightly in their cardiac dysfunction.<sup>21,22</sup> However, somewhat surprisingly, both lines appear to have close to normal mitochondrial volume density in the heart<sup>21,22</sup> yet the expression of mitochondrial genes is blunted.<sup>22</sup> Chronic haemodynamic overload in these mice induces accelerated cardiac dysfunction accompanied by overt clinical signs of heart failure, indicating that decreased PGC-1 $\alpha$  expression may play a significant role in the development of heart failure.<sup>23</sup> However, the maintenance of the mitochondrial volume fraction suggests that additional mechanisms controlling mitochondrial biogenesis exist.

PGC-1 $\alpha$  is the first-discovered member of a family of three related proteins that control major metabolic functions. Whereas the PGC-1-related co-activator (PRC) is expressed ubiquitously, PGC-1 $\alpha$  and  $\beta$  are enriched in mitochondria-rich tissues such as cardiac and skeletal muscles. Overexpression studies suggest that PGC-1 $\alpha$  and  $\beta$  exert specific bioenergetic effects, with PGC-1 $\beta$  preferentially inducing genes involved in the removal of reactive oxygen species.<sup>24</sup> Deficiency in PGC-1 $\beta$  in the heart results in a general defect in the expression of genes encoding components of the electron transport chain and in a reduced mitochondrial volume fraction, leading to a blunted response to dobutamine stimulation.<sup>25</sup> However, only PGC-1 $\alpha$  seems to respond to metabolic challenges such as exercise, starvation or cold, suggesting that PGC-1 $\beta$  could play a role in constitutive mitochondrial biogenesis.<sup>26</sup>

### 2.4 Additional targets of PGC-1 $\alpha$

In addition to NRFs, PGC-1 $\alpha$  also interacts with and co-activates other transcription factors like PPARs, thyroid hormone, glucocorticoid, estrogen, and estrogen-related ERR $\alpha$  and  $\gamma$  receptors (Figure 2). The two orphan nuclear



**Figure 2** PGC-1 $\alpha$  regulatory cascade. Thyroid hormone (TH), nitric oxide synthase (NOS/cGMP), p38 mitogen-activated protein kinase (p38MAPK), sirtuins (SIRT6), calcineurin, calcium-calmodulin-activated kinases (CaMKs), adenosine-monophosphate-activated kinase (AMPK), cyclin-dependent kinases (CDKs), and  $\beta$ -adrenergic stimulation ( $\beta$ /cAMP) have been shown to regulate expression and/or activity of PGC-1 $\alpha$ . PGC-1 $\alpha$  then co-activates transcription factors such as nuclear respiratory factors (NRFs), estrogen-related receptors (ERRs), and PPARs, known to regulate different aspects of energy metabolism including mitochondrial biogenesis, fatty acid oxidation, and antioxidant.

receptors ERR $\alpha$  and  $\gamma$  target a common set of promoters involved in the uptake of energy substrates, production, and transport of ATP across the mitochondrial membranes, and intracellular fuel sensing.<sup>27</sup> Ablation of ERR $\alpha$  induces signs of heart failure in mice subjected to left ventricular pressure overload, indicating that ERR $\alpha$  is required for the adaptive bioenergetic response.<sup>28</sup> In contrast, ERR $\gamma$  deficiency was recently shown to induce complex cardiac defects in embryos involving changes in the expression of genes involved in mitochondrial biogenesis, suggesting a possible role for ERR $\gamma$  in the postnatal transition to oxidative metabolism and fatty acid utilization.<sup>29</sup>

The PPAR family of transcription factors plays a major role in the expression of proteins involved in extra and intramitochondrial fatty acid transport and oxidation (FAO). All PPARs are expressed in the myocardium, although PPAR $\alpha$  and  $\beta/\delta$  are the main cardiac isoforms. PPAR $\alpha$  binds its obligate partner the retinoid-X-receptor (RXR), and the resulting heterodimer is involved in the regulation of enzymes, transporters, and proteins of FAO.<sup>19</sup> The activity of the PPAR/RXR complex is modulated by the availability of ligands, the most relevant of which are long-chain fatty acids and their metabolites. FAO is increased in cardiomyocytes exposed to PPAR $\alpha$  and PPAR $\beta/\delta$  ligands, but not PPAR $\gamma$  ligands, consistent with the PPAR isoform expression pattern in heart tissue.<sup>30</sup> PGC-1 $\alpha$  cooperates with PPAR $\alpha$  to regulate expression of mitochondrial FAO enzymes and transport proteins, thus enabling increases in FAO pathway activity to be coordinated with mitochondrial biogenesis.<sup>31</sup> PPAR $\beta/\delta$  plays also a prominent role in the regulation of cardiac lipid metabolism. Cardiomyocyte-restricted PPAR $\beta/\delta$  deletion perturbs myocardial FAO and leads to lipotoxic cardiomyopathy.<sup>32</sup> However, because PPAR $\beta/\delta$  null mice do not exhibit a fasting-induced phenotype, it was proposed that these isoforms probably serve to regulate basal metabolism,

whereas PPAR $\alpha$  is involved in the response to physiological conditions that stimulate FA delivery.<sup>33</sup> Among the two PPAR $\gamma$  isoforms, PPAR $\gamma$ 1 is predominantly expressed in the heart. Cardiomyocyte-specific PPAR $\gamma$ 1-KO mice develop cardiac hypertrophy with preserved systolic function and signs of heart failure that develop with aging, together with the abnormal mitochondrial structure,<sup>34</sup> suggesting that PPAR $\gamma$  could also play a role in mitochondrial biogenesis. However, it is not yet firmly established whether the mitochondrial defects observed in these studies result directly from deletion of PPARs or whether they are secondary effects of the cardiac phenotype.

Mitochondrial biogenesis thus involves an intricate, complicated network of transcription factors NRFs/PPARs/ERRs that activate target genes encoding enzymes of FAO, oxidative phosphorylation, and anti-oxidant defences (Figure 2). PGC-1 $\alpha$ , by co-activating, and controlling the expression of this network, directly links external physiological stimuli to the regulation of mitochondrial biogenesis and function. Additionally, mitochondrial biogenesis involves fusion/fission and requires protein import and processing and cardiolipin biosynthesis. Whether the transcriptional regulation of these processes involves the same or similar transcription cascades is still largely unknown, although in skeletal muscle, PGC-1 $\alpha$ , and mitochondrial content correlate strongly with expression of certain proteins involved in mitochondrial dynamics and protein processing.<sup>8</sup>

### 3. Signalling pathways involved in PGC-1 $\alpha$ activity

A large number of signalling pathways have been proposed to regulate PGC-1 $\alpha$  (Figure 2).

### 3.1 Calcium- and second messenger-dependent regulation of PGC-1 $\alpha$ expression

Increased contractile activity translates into a sustained increase in intracellular calcium concentration, which activates the calcium-dependent phosphatase calcineurin (CaN) and Ca<sup>2+</sup>-calmodulin dependent kinase (CaMK).<sup>35</sup> CaN controls the expression of PGC-1 $\alpha$  in muscle, providing a calcium-signalling pathway whose stimulation results in increased mitochondrial content.<sup>36</sup> Loss of calcineurin in heart results in impaired mitochondrial electron transport associated with high levels of superoxide production.<sup>37</sup> Moreover, in early embryonic development, the dephosphorylation of nuclear factors of activated T cells (NFATs) by calcineurin is required for mitochondrial energy metabolism.<sup>38</sup> Transcriptional profiling studies demonstrated that CaN and CaMK activate distinct but overlapping metabolic gene regulatory programs.<sup>39</sup> CaN, but not CaMK, activates the mouse PPAR $\alpha$  promoter, indicating that FAO genes are selectively activated by CaN. CaN-mediated PGC-1 $\alpha$  promoter activation is dependent on myocyte enhancer factor-2 (MEF2) activity and the histone deacetylases (HDACs). Expression of a signal-resistant form of HDAC in mouse heart results in loss of mitochondria and changes in their morphology.<sup>40</sup> MEF2, which is stimulated by CaN signalling, binds to the PGC-1 $\alpha$  promoter and activates it, predominantly when co-activated by itself.<sup>36</sup> Deletion of MEF2A in mice results in perturbation of mitochondrial structure and significant loss of mitochondria.<sup>41</sup> CaMK activation of PGC-1 $\alpha$  expression requires the cAMP response element-binding protein (CREB).<sup>42</sup> Moreover, the transducer of regulated CREB-binding protein (TORC) may enhance CREB-dependent PGC-1 $\alpha$  transcription.<sup>43</sup> In the heart in response to both physiological and pathological hypertrophic stimuli, there is a strong positive correlation of CREB activation with PGC-1 $\alpha$  expression and mitochondrial respiratory rate and protein content.<sup>44</sup> Interestingly, DrPp1 expression correlates with the PGC-1 $\alpha$  content and calcineurin activation in human skeletal muscle,<sup>8</sup> and dephosphorylation of Drp1 by CaN induces its translocation to mitochondria thus triggering mitochondrial fission.<sup>45</sup>

Activation of the p38 mitogen-activated protein kinase (MAPK) pathway in skeletal muscle has been shown to promote PGC-1 $\alpha$  expression. However, the cardiac mitochondria of transgenic mice overexpressing the p38MAPK upstream kinase MAPK-kinase-6 (MKK6) have lower oxidative respiration and decreased generation of reactive oxygen species,<sup>46</sup> suggesting that p38MAPK is involved in the negative regulation of mitochondrial biogenesis.

Treatment of various cells with NO donors increases their mtDNA content, and this is sensitive to removal of NO by NO scavengers.<sup>47</sup> The effects of NO occur via increased expression of PGC-1 $\alpha$  and its down-stream effectors, and depend on the second messenger cGMP by activation of particulate guanylyl cyclase. Tissues of eNOS<sup>-/-</sup> mice such as the brain, liver, muscle and heart have a slightly decreased content of some mitochondrial proteins.<sup>47</sup> However, oxidative capacity and mitochondrial enzymes are not altered in hearts of eNOS<sup>-/-</sup> mice, suggesting that eNOS is not involved in cardiac basal mitochondrial biogenesis.<sup>48</sup> However, eNOS may be necessary for the cardiac response to stress, since caloric restriction involves an eNOS-dependent increase in cardiac mitochondrial biogenesis.<sup>49</sup>

### 3.2 Energy-dependent regulation of PGC-1 $\alpha$ activity

It has been proposed that the phylogenetically conserved AMP-dependent serine/threonine protein kinase (AMPK) plays a role in skeletal muscle-induced mitochondrial biogenesis. PGC-1 $\alpha$  is induced by exercise and by chemical activation of AMPK in skeletal muscle (for review see Reznick and Shulman<sup>50</sup>). Activation of AMPK and mitochondrial biogenesis in muscle in response to chronic energy deprivation is diminished in AMPK $\alpha$ 2-kinase-dead mice, revealing the importance of AMPK in this response.<sup>51</sup> Indeed, cardiac mitochondrial respiration is altered in mice lacking the main catalytic subunit of cardiac and skeletal muscle AMPK (AMPK $\alpha$ 2-/-) by a mechanism that involves decreased cardiolipin biosynthesis,<sup>52</sup> suggesting that AMPK is involved in cardiolipin biosynthesis. However, there are no changes in mitochondrial markers or PGC-1 $\alpha$  expression in the hearts of these mice.<sup>52,53</sup>

Sirtuins are highly conserved NAD<sup>+</sup>-dependent deacetylases recently shown to control lifespan. Increased lifespan is associated with augmented mitochondrial oxidative phosphorylation and aerobic capacity. Resveratrol, a polyphenol that was shown to extend lifespan, increases aerobic capacity in mice and induces expression of genes that encode proteins involved in oxidative phosphorylation and mitochondrial biogenesis. These effects occur via a SIRT-1-dependent increase in PGC-1 $\alpha$  expression in skeletal muscle and adipose tissue, although not in heart.<sup>54</sup> Interestingly, caloric restriction-induced mitochondrial biogenesis in heart is accompanied by increased SIRT1 expression in wild-type but not eNOS<sup>-/-</sup> mice.<sup>49</sup> These results again indicate that mitochondrial biogenesis is strictly controlled in the heart.

### 3.3 Hormonal control of PGC-1 $\alpha$

Thyroid hormones (TH) drastically alter the expression of nuclear- and mitochondria-encoded genes in several tissues. TH can control mammalian mitochondrial biogenesis through direct and indirect pathways. The direct pathway involves the binding of TH receptors (TR $\alpha$  and  $\beta$ ) on TRE recognition sites on nuclear-encoded mitochondrial genes, and activation of the mitochondrial genome via a truncated form of TR $\alpha$  called p43.<sup>55</sup> However, of the nuclear genes necessary for the biogenesis of mitochondria, only a few respond directly to thyroid hormone.<sup>11</sup> An indirect pathway involves the control of PGC-1 $\alpha$  expression, and activation of its downstream transcription cascade.<sup>56</sup> However, the effects of TH on mitochondrial content in the adult heart are not clear. Indeed, one study found that TH treatment of rats increased cardiac oxygen consumption, mitochondrial bioenergetic capacity and expression of markers of mitochondrial biogenesis such as PGC-1 $\alpha$  and its transcription cascade.<sup>57</sup> In contrast, other studies (including our own unpublished results) found no change in PGC-1 $\alpha$  myocardial expression/activity with TH treatment.<sup>58</sup> Interestingly, an interaction between PGC-1 $\alpha$  and thyroid hormone receptors has been reported.<sup>59</sup> Hypothyroidism induces a decrease in the maximal oxidative capacity and expression/activity of mitochondrial enzymes in cardiac muscle, which is independent of PGC-1 $\alpha$  and its transcription cascade, suggesting that there exists a unique mode of regulating mitochondrial respiration by TH.<sup>60</sup> Additionally, thyroid hormones control cardiolipin biosynthesis and regulate the mitochondrial

protein import machinery, thus providing another ways of regulating mitochondrial function.<sup>9,61,62</sup>

### 3.4 Cyclin-dependent kinases

Cyclin-dependent kinases (CDKs) are involved in cell cycle and/or transcriptional control. Gene expression profiling studies demonstrated that, cyclinT/Cdk9, an RNA polymerase kinase involved in cardiac hypertrophy, suppresses the expression of many genes that encode mitochondrial proteins such as PGC-1 $\alpha$  and its downstream effectors.<sup>63</sup> In addition, the Cdk7/cyclinH/ménage-à-trois-1 (MAT1) heterotrimer is activated in adult hearts by stress-dependent pathways for hypertrophic growth. Ablation of MAT1 causes suppression of genes involved in energy metabolism as well as the PGC-1 $\alpha$  and  $\beta$  genes, indicating that a requirement exists for MAT1 in the operation of PGC-1 that control cardiac metabolism.<sup>64</sup>

### 4. Posttranslational control of PGC-1 $\alpha$

In addition to their regulated expression by various metabolic stimuli, the family of PGC-1 co-activators is controlled by post-translational modifications. PGC-1 $\alpha$  phosphorylation by p38MAPK, for example, is most likely involved in mediating the effects of cytokines.<sup>65,66</sup> An interesting observation made recently is that, in addition to increasing PGC-1 $\alpha$  expression, AMPK can directly phosphorylate PGC-1 $\alpha$ , this phosphorylation being required for the PGC-1 $\alpha$ -dependent induction of the PGC-1 $\alpha$  promoter.<sup>67</sup> Another important post-translational modification of PGC-1 $\alpha$  is the deacetylation induced by the NAD<sup>+</sup>-dependent SIRT1 deacetylase.<sup>68</sup> In skeletal muscle, SIRT1-induced deacetylation of PGC-1 $\alpha$  is required for activation of mitochondrial fatty acid oxidation

genes in response to fasting and low glucose.<sup>69</sup> In the heart, SIRT1 regulates aging and resistance to oxidative stress.<sup>70</sup> PGC-1 $\alpha$  activity is also potentiated by arginine methylation, which is catalysed by protein arginine methyltransferase-1 (PRMT1), another nuclear receptor co-activator. Mutation of three arginine residues in the C-terminal region of PGC-1 $\alpha$  compromises the ability of PGC-1 $\alpha$  to induce expression of endogenous target genes.<sup>71</sup> These forms of post-translational regulation of PGC-1 $\alpha$  activity are additional mechanisms that link mitochondrial biogenesis with intracellular signalling pathways, thereby increasing the complex regulation of oxidative metabolism.

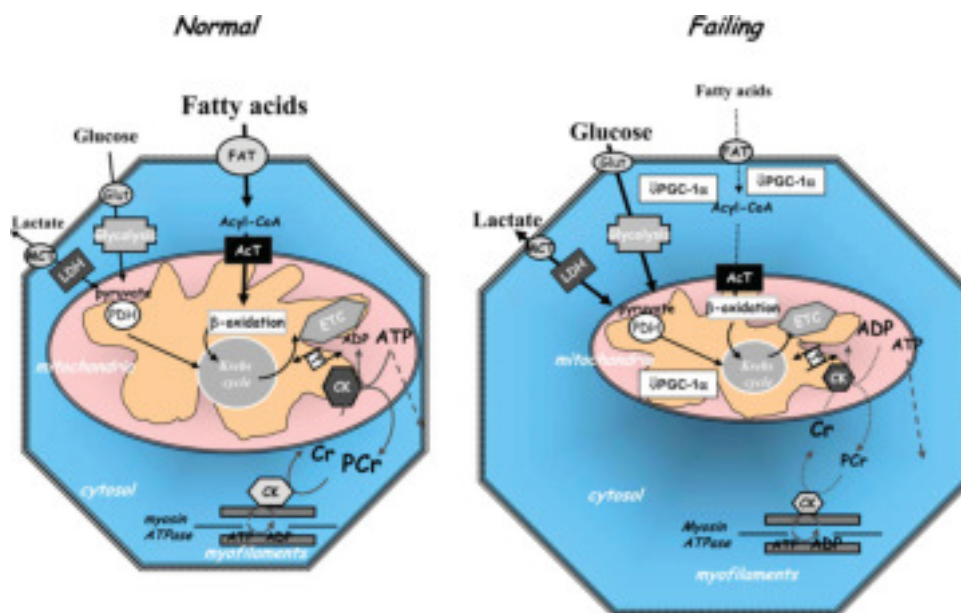
## 5. Mitochondrial biogenesis and cardiovascular diseases

The energetic failure of the hypertrophied and failing heart has been extensively reviewed elsewhere (for example see reference<sup>72-76</sup>). Briefly, as summarized in Figure 3, the energetic changes include (i) an early switch in substrate utilization from fatty acids to glucose, (ii) decreased oxidative capacity and energy production due to decreased mitochondrial biogenesis, (iii) decreased energy transfer by the phosphotransfer kinases, (iv) altered energy utilization, and (v) decreased efficiency of energy consumption. The signalling and molecular origins of these defects are largely unknown.

### 5.1 Hypertrophy and heart failure

#### 5.1.1 Physiological hypertrophy and mitochondrial biogenesis

The adaptation of cardiac muscle to training involves cardiomyocyte remodelling and hypertrophy. Recent studies present evidence that exercise training increases expression



**Figure 3** Cardiomyocyte energy metabolism. (A) Normal cardiomyocyte. Cardiomyocyte mainly uses fatty acids that enter the cell membrane through fatty acid transports (FAT) at the cell membrane and (CPT) at the mitochondrial membrane before being used by  $\beta$ -oxidation and electron transport chain (ETC) to produce ATP. Glucose and lactate enter through their respective transporters (GLUT and MCT) and are transformed into pyruvate by glycolysis and lactate dehydrogenase (LDH), respectively. Pyruvate enters the Krebs cycle to produce ATP. ATP is then converted into phosphocreatine by mitochondrial creatine kinase (CK). Phosphocreatine is used by localized CK close to ATPases to rephosphorylate ADP. (B) Failing cardiomyocyte. In heart failure, fatty acid utilization is blunted, mitochondrial activity decreases and ATP synthesis is impaired. Moreover, decreased CK expression compromises energy transfer within the cardiomyocyte. The possible sites of action of PGC-1 $\alpha$  are indicated.

of PGC-1 $\alpha$  and its downstream cascade, at least during hypertrophic growth.<sup>44,77</sup> Whether or not exercise training is accompanied by a sustained increase in mitochondrial content independent of cardiac hypertrophy is not at all clear. In animal models, some studies showed that regular endurance exercise increases glycolysis and oxidative metabolism, whereas others demonstrated that adaptive responses result from increased muscle mass rather than changes in mitochondrial gene expression (see Ventura-Clapier *et al.*<sup>78</sup> for review). This could be related to the existence of an already 'optimal' basal level of mitochondrial content in adult heart as a result of an optimized contractile protein/mitochondria ratio.

### 5.1.2 Pathological hypertrophy and heart failure

It is now widely accepted that FAO enzymes and other mitochondrial proteins are down-regulated in the failing heart.<sup>18,79</sup> The group of Kelly has done extensive work on the dynamic regulation of the cardiac PPAR/PGC-1 $\alpha$  complex and its control of cardiac mitochondrial energy production following the onset of pathological cardiac hypertrophy. During pathological growth of the heart, downregulation of PPAR $\alpha$  and PGC-1 $\alpha$  causes decreased expression of FAO genes.<sup>80</sup> In our research on the origin of decreased cardiac muscle oxidative capacity in the pathogenesis of heart failure, we have shown that the decrease in mitochondrial function in both cardiac and skeletal muscle following pressure overload is linked to the down-regulation of PGC-1 $\alpha$  and its downstream effectors, NRF2 and Tfam.<sup>18</sup> Similar findings have now been reported in a number of other models of heart failure, including the muscle LIM protein-null mouse,<sup>81</sup> rats with myocardial infarction,<sup>82–85</sup> spontaneously hypertensive rats, and a mouse model of hypertrophic cardiomyopathy.<sup>44</sup> Recently, downregulation of the PPAR/PGC-1 $\alpha$  complex and of its targets was reported in failing human hearts.<sup>86</sup> Interestingly, single polymorphisms in the PGC-1 $\alpha$  gene have been identified which correlate with an increased risk of hypertrophic cardiomyopathy.<sup>87</sup> This suggests that the decreased expression of the PGC-1 $\alpha$ /PPAR $\alpha$  transcription cascade is the molecular basis for energy starvation of the failing myocardium.

### 5.1.3 Signalling pathways for downregulation of PGC-1 $\alpha$ in HF

The molecular mechanisms underlying the loss of PGC-1 $\alpha$ /PPAR in heart failure are poorly understood. Indeed, the main signalling pathways involved in mitochondrial biogenesis, such as MAPK, calcineurin, cAMP-dependent signalling, and AMPK, are considered to be up- rather than down-regulated in pathological hypertrophy and heart failure.<sup>88,89</sup>

Similarities between the changes in cardiac gene expression in pathological hypertrophy and hypothyroidism led to the hypothesis that a reduction in thyroid hormone plays a role in the development of metabolic and functional alterations in these conditions. Indeed, HF is accompanied by low or subclinical blood levels of thyroid hormone, altered expression of thyroid receptors,<sup>90</sup> and increased cellular degradation of thyroid hormones.<sup>91</sup> However, hypothyroidism induces a metabolic pattern that differs from heart failure, suggesting that HF-induced downregulation and deactivation of PGC-1 $\alpha$  is not, in fact, due to cellular hypothyroidism.<sup>60</sup> Elevated Akt activity has been demonstrated in the failing heart,<sup>88</sup> and overexpression of

Akt has been shown to induce a 3-fold downregulation of PGC-1 $\alpha$  gene expression.<sup>92</sup> The downregulation of mitochondrial transcription factors induced by postinfarction remodelling can be significantly attenuated by Na<sup>+</sup>/H<sup>+</sup> exchanger-1 inhibition, and mitochondrial function is improved by changes in the regulation of Akt activity.<sup>85</sup> Chronic activation of Cdk9 in HF causes defective mitochondrial function, via loss of PGC-1 $\alpha$ .<sup>63,93</sup>

Studies to determine the role of calcineurin in cardiac hypertrophy and heart failure have produced contradictory results, showing either calcineurin activation or no change or a decrease in calcineurin activity.<sup>88,94</sup> Despite the importance of CREB for transcriptional activation of PGC-1 $\alpha$ , treating cardiac cells in culture with catecholamine, which stimulates adenylate cyclase, leads to repression of PGC-1 $\alpha$  and many of its target genes which can be reversed by ectopic expression of PGC-1 $\alpha$ .<sup>23</sup> On the other hand, in spontaneously hypertensive rats, decreased CREB phosphorylation strongly correlates with expression of PGC-1 $\alpha$  and mitochondrial protein content,<sup>44</sup> indicating decreased rather than increased cAMP-dependent gene activation. At present nothing is known about the post-translational modification of PGC-1 $\alpha$  in HF.

## 5.2 Diabetes, insulin resistance, and obesity

Obesity and diabetes are complex metabolic syndromes in which cardiac disease is a significant cause of mortality. Recent studies have shown that mitochondrial function is altered in the hearts of diabetic animals. In type I diabetes, there is a decrease in PGC-1 mRNA expression,<sup>95</sup> whereas in the insulin-resistant heart mitochondrial biogenesis occurs driven by the PPAR $\alpha$ /PGC-1 $\alpha$  gene regulatory pathway.<sup>96</sup> In addition, cardiolipin depletion has been observed in diabetic myocardium using shotgun lipidomics, thus linking altered substrate utilization with mitochondrial dysfunction.<sup>97</sup> Mitochondrial damage and decreased mitochondrial density and mtDNA content in high-fat diet-induced obesity are closely associated with downregulation of PGC-1 $\alpha$  and its downstream cascade.<sup>98</sup> Cardiac changes in this pathology also include defects in mitochondrial function, lipid oxidation, and mitochondrial biogenesis leading to cardiac lipotoxicity, possibly involving eNOS-dependent NO production.<sup>99</sup>

## 5.3 Ischaemia

Evidence have been accumulating that protection against ischaemic damage could be linked to mitochondrial biogenesis (see McLeod *et al.*<sup>100</sup> for review). Preconditioning is an intervention that causes attenuation of ischaemic damage. Following delayed preconditioning, mitochondria display increased tolerance to anoxia-reperfusion injury associated with increased biogenesis (induction of PGC-1 $\alpha$  and NRF-1) and expression of mitochondrial proteins.<sup>101</sup> Other indirect evidence supports a mechanistic link between ischaemic preconditioning and mitochondrial biogenesis. The preconditioning-mimetic diazoxide activates the mitochondrial biogenesis regulatory protein CREB.<sup>102</sup> Moreover, NO, a trigger of preconditioning, also directly activates the mitochondrial biogenesis program. Mitochondrial biogenesis also upregulates a broad spectrum of ROS detoxification systems,<sup>24</sup> providing a mechanism by which the mitochondrial biogenesis

program may additionally augment tolerance to cardiac ischaemia.

## 6. Conclusions

Mitochondria are of the utmost importance for cardiac function. Forced activation of mitochondrial biogenesis in the adult heart results in heart failure, suggesting that there is an optimal mitochondrial volume. Mitochondrial biogenesis involves multiple processes that need to be tightly coordinated. It appears that the co-activator PGC-1 $\alpha$ , the master regulator of mitochondrial biogenesis, plays a role in coordinating the growth of the mitochondrial compartment. Energy starvation and decreased expression/activity of the PGC-1 $\alpha$  transcription cascade are hallmarks of cardiac dysfunction, which lead to impaired energy metabolism and which contribute to contractile failure. Many signalling pathways have been shown to be involved in mitochondrial biogenesis. Whether they directly control PGC-1 $\alpha$  expression or whether impaired energy metabolism is a secondary consequence of the complex overlap of energy metabolism with cardiac function remains to be determined. More work is needed in this growing area, but the PGC-1 $\alpha$  axis could be envisioned as a new, exciting therapeutic target in metabolic disorders and heart failure.

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