Mitochondrial response to nutrient availability and its role in metabolic disease

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Abstract

Metabolic inflexibility is defined as an impaired capacity to switch between different energy substrates and is a hallmark of insulin resistance and type 2 diabetes mellitus (T2DM). Hence, understanding the mechanisms underlying proper metabolic flexibility is key to prevent the development of metabolic disease and physiological deterioration. An important downstream player in the effects of metabolic flexibility is the mitochondrion. The objective of this review was to describe how mitochondrial metabolism adapts to limited nutrient situations or caloric excess by changes in mitochondrial function or biogenesis, as well as to define the mechanisms propelling these changes. Altogether, this should pinpoint key regulatory points by which metabolic flexibility might be ameliorated in situations of metabolic disease.

Keywords caloric restriction; diabetes; high-fat diet; metabolic disease; mitochondrial dynamics

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In this review, we aim to integrate the current knowledge on these areas and address three key questions: (i) What is the evidence for mitochondrial dysfunction in acquired metabolic disorders? (ii) How does energy stress impact on mitochondrial function, for instance at the level of biogenesis (AMPK/sirtuins) and mitochondrial dynamics (fusion/fission/mitophagy)? (iii) Is mitochondrial function a realistic target for pharmacological or nutritional intervention for the treatment of metabolic diseases?

Deficient metabolic flexibility as a cause for metabolic disease

The capacity of an organism, an organ, or a single cell to adapt fuel oxidation to fuel availability is termed metabolic flexibility (Galgani et al., 2008). This nomenclature was proposed as the capability to switch from fat metabolism in a fasting state to suppression of fat oxidation and enhanced glucose metabolism upon stimulation by insulin (Kelley & Mandarino, 2000). Active storage of nutrients and efficient disposal of blood glucose after a meal are characteristic of healthy metabolism (Storlien et al., 2004). In turn, metabolically inflexible individuals fail to adapt their fuel preference to changes in carbohydrate or lipid supplies (Galgani et al., 2008).

Imbalanced energy homeostasis is a characteristic of obese and type 2 diabetes mellitus (T2DM) patients. Interestingly, metabolic inflexibility can already be observed in pre-diabetic individuals suffering from insulin resistance (Corpeleijn et al., 2009), limiting the ability to switch from fatty acid breakdown to fat storage after a meal and vice versa (Kelley, 2005). Diverse mitochondrial parameters vary between insulin-resistant and insulin-sensitive subjects, such as mitochondrial number, structure, and function. This suggests that mitochondrial dysfunction might contribute to metabolic inflexibility and insulin resistance (Galgani et al., 2008).

Mitochondrial deficiencies limit the capacity of oxidative tissues to adapt fat oxidation to fat availability, leading to the accumulation of lipids in non-adipose tissues, such as skeletal muscle. Intramyocellular lipids (IMCL) are used as fuel during regular exercise (Coen & Goodpaster, 2012), but lipid accumulation in non-adipose tissues is also highly associated with insulin resistance (Canto &
Despite having a 30% lower mitochondrial content, have higher insulin resistance only after prolonged high-fat feeding, while insulin resistance was also characteristic in age-related insulin resistance (Petersen et al., 2003; Patti et al., 2006; Pospisilik et al., 2008). Along the same line, insulin-stimulated glucose uptake in muscle (Pan et al., 1997). The link between IMCL and insulin resistance was confirmed in biopsies from individuals with obesity and T2DM (Goodpaster et al., 2000; Coen & Goodpaster, 2012). In obese individuals, impaired mitochondrial function might contribute to lower IMCL turnover and lead to lipotoxicity (Schooneman et al., 2013). These lipids interfere with insulin signaling and represent one of the key aspects that could contribute to insulin resistance in situations of high-fat feeding or lipid infusion (Pan et al., 1997; Krssak et al., 1999; Goodpaster et al., 2000).

Gene-clustering approaches supported the above hypothesis by demonstrating that muscles from T2DM patients display downregulation of lipid oxidation and mitochondrial metabolism genes (Mootha et al., 2003; Patti et al., 2003). Mitochondrial deficiencies were also characteristic in age-related insulin resistance (Petersen et al., 2003). In a parallel study, insulin resistance in the skeletal muscle of insulin-resistant offspring of T2DM patients was associated with dysregulation of intramyocellular fatty acid metabolism, possibly due to deficiencies in mitochondrial oxidative phosphorylation capacity (Petersen et al., 2004). In light of the above data, increasing mitochondrial content could constitute a promising preventive and therapeutic approach against insulin resistance and T2DM (Canto & Auwerx, 2009). Several pharmacological and nutritional interventions have been designed in this direction, which protect against the development of insulin resistance and high-fat diet (HFD)-induced metabolic damage (e.g., resveratrol or PPARβ agonists) (Andreux et al., 2013).

Although the correlative evidence around mitochondrial dysfunction and the development of metabolic diseases is overwhelming, some evidence casts a shadow of doubt on its causal role. For instance, some of the mouse models that overexpress proteins promoting mitochondrial biogenesis display a largely enhanced mitochondrial content in skeletal muscle, but are insulin resistant (Finck et al., 2005; Choi et al., 2008). Along the same line, insulin-stimulated glucose sensitivity is increased in some mouse models of mitochondrial dysfunction (Wredenberg et al., 2006; Pospisilik et al., 2007; Zechner et al., 2010). Also, mitochondrial dysfunction is observed only after prolonged high-fat feeding, while insulin resistance develops earlier (Hancock et al., 2008). Finally, T2DM patients, despite having a 30% lower mitochondrial content, have higher mitochondrial oxidation rates and do not have an intrinsic problem to increase their whole-body fat oxidation rate during exercise (Larsen et al., 2009; Holloszy, 2013). Similarly, the decreased mitochondrial content in insulin-resistant old individuals seems to be rather linked to decreased physical activity and can be perfectly enhanced in response to exercise (Broskey et al., 2014). This highlights how some tissues, such as human muscle, might actually have a notable reserve of respiratory capacity, and that minor changes in their mitochondrial content might not be enough to limit resting respiratory needs. Indeed, the concept of reserve respiratory capacity in humans is not new. It was initially characterized in diverse human cell lines, where COX activity was found to be higher than that required to support endogenous respiration rates, allowing this way some adaptability to higher respiratory needs (Villani et al., 1998). Therefore, while many strategies to increase mitochondrial function rendered protection against insulin resistance and T2DM, further studies are required to clarify the link between mitochondrial deficiency and insulin resistance. Furthermore, future studies will have to address mitochondrial functional quality rather than quantity, as will become apparent in the following sections.

Mechanisms controlling mitochondrial metabolism

In order to maintain metabolic homeostasis, organisms adjust the capacity and efficiency of ATP generation to changes in energetic demand and supply. Mitochondrial activity can be controlled through at least two major mechanisms: acute ones, aimed to qualitatively modify mitochondrial function, and longer-term transcriptional mechanisms, aimed to increase mitochondrial number.

Acute mechanisms for the control of mitochondrial metabolism

Acute mechanisms to modify mitochondrial function affect the intrinsic ability of mitochondria to generate ATP per molecule of nutrient or per unit of time. Two major mechanisms have potently emerged, namely changes in mitochondrial architecture or dynamics, and regulation through post-translational mechanisms.

Mitochondrial dynamics Changes in mitochondrial architecture are dynamic and involve a delicate balance between proteins promoting fusion [e.g., mitofusin (Mfn) 1 and Mfn2, and optic atrophy 1 (Opa1)] and fission [e.g., fission 1 (Fis1)], mitochondrial fission

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factor (Mff), and dynamin-related protein 1 (Drp1)] (Youle & van der Bliek, 2012). Cells under a well-fed condition maintain their mitochondria in a separated (or fragmented) state, while under fasting or starved conditions, mitochondria tend to persist in a connected (or fused) state (Gomes et al., 2011). This suggests that adaption of bioenergetics involves remodeling of mitochondrial architecture. Indeed, as described below, changes in mitochondrial architecture can affect respiratory complex assembly and the proper coupling of respiration to ATP synthesis (Gomes et al., 2011). In addition, the transitions between fragmented and fused states allow mitochondria to reorganize and dispose damaged elements through mitophagy (Fig 1). Notably, the mitochondrial life cycle is attenuated when the fusion or fission pathways are not functioning properly, leading to mitochondrial dysfunction. Dysfunctional mitochondria, especially those with dissipated membrane potential, are recognized by the mitophagic machinery and broken down rapidly (Youle & Narendra, 2011). Thus, mitochondrial architectural changes might offer a new molecular mechanism to connect nutrient availability to bioenergetic adaptations (Liesa & Shirihai, 2013).

Post-translational modifications Among different post-translational modifications, protein acetylation has recently emerged as another reversible mechanisms linking the metabolic state and mitochondrial function (Figs 2A and 3A). Mitochondria contain many acetylated proteins, often at several residues. Reversibly acetylated mitochondrial proteins can be found in most mitochondrial functions, including oxidative phosphorylation (Ahn et al., 2008), reactive oxygen species metabolism (Qiu et al., 2010; Chen et al., 2011) and fatty acid metabolism (Hirschey et al., 2010). Upon fasting and high-fat feeding, the acetylation pattern of mitochondrial proteins strongly changes. This is due to changes in the balances between acetylation and deacetylation rates, for instance involving

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**Figure 1.** Mitochondrial dynamics and quality control.
Mitochondrial dynamics involves repetitive cycles of mitochondrial fusion and fission. Fusion of mitochondria is regulated by mitofusin (Mfn) 1 and Mfn2 (both proteins are required for mitochondrial outer membrane fusion) and optic atrophy 1 (Opa1) (required for mitochondrial inner membrane fusion protein). Mitochondrial fission is regulated by dynamin-related protein 1 (Drp1), mitochondrial fission factor (Mff), and fission 1 (Fis1). When a daughter mitochondrion is dysfunctional/depolarized, it will be targeted for elimination. The defective mitochondria accumulate tensin homolog-induced putative kinase protein 1 (PINK1) at the mitochondrial surface, which in turn recruits Parkin. Parkin-induced ubiquitylation of the outer membrane initiates the recruitment of autophagosomes, which are degraded after fusion with a lysosome.
the mitochondrial NAD⁺-dependent deacetylase SIRT3 (Houtkooper et al., 2012). This opens the possibility that coordinated changes in mitochondrial acetylation serve to regulate mitochondrial acetyl-CoA levels and trigger appropriate responses. Therefore, understanding the specificity of mitochondrial acetylation dynamics will be a key to evaluate the impact of nutritional states on mitochondrial function. In addition to acetylation, novel mitochondrial post-translational modifications have emerged that may reflect the metabolic state, including succinylation and malonylation (Du et al., 2011; Peng et al., 2011). Although the physiological role of these modifications is not yet understood, its reliance on the NAD⁺-dependent deacetylation, which is further enhanced by a concurrent increase in NAD⁺ levels.

Transcriptional regulation of mitochondrial metabolism

Cellular oxidative capacity can also be controlled through increasing its mitochondrial content. Mitochondrial biogenesis is achieved through orchestrated induction of several transcriptional regulators, whose activity is critically determined by energetic demands (Andreux et al., 2013) (Figs 2B, 3B and C). A key family of transcription factors that connect lipid metabolism with transcriptional outputs is the PPARs. PPARs are nuclear receptors that directly bind specific lipid species that generally increase upon cellular fat overflow in the cells. There are three PPARs: α, β (also known as δ) and γ. Each of these binds specific lipid species as ligands and controls different transcriptional programs linked to lipid metabolism (Wahl & Michalik, 2012). For example, PPARα activates fatty acid oxidation by inducing lipid oxidation genes in mitochondria and peroxisomes (Yoon, 2009). PPARβ/δ triggers fatty acid β-oxidation in muscle and adipose tissue, which results in enhanced fat breakdown (Wang et al., 2003; Varga et al., 2011). In contrast, PPARγ controls lipogenic and adipocyte differentiation gene expression and activates lipid storage (Varga et al., 2011; Wahl & Michalik, 2012).

The PPARγ coactivator 1α, PGC-1α, regulates mitochondrial biogenesis by coactivating various transcription factors and nuclear receptors. The activity of PGC-1α is regulated by post-translational modifications that fine-tune mitochondrial metabolism with environmental challenges (Canto & Auwerx, 2009). For example, PGC-1α activity is determined by its acetylation status. In the basal state, PGC-1α is acetylated, which dampens PGC-1α activity. Upon nutrient stress, the NAD⁺-dependent deacetylase SIRT1 activates PGC-1α, a reaction that is rate-limited by availability of the metabolite NAD⁺ (Houtkooper et al., 2010a). Hence, increasing NAD⁺ content leads to higher SIRT1 activity (Canto & Auwerx, 2012). NAD⁺ is a highly dynamic molecule whose cellular abundance depends on the metabolic state. Therefore, SIRT1 is optimally positioned to translate the metabolic state to transcriptional outputs on mitochondrial biogenesis through the deacetylation of PGC-1α. Indeed, different situations of energy restriction, including fasting and exercise, increase NAD⁺ levels and trigger SIRT1/PGC-1α-dependent mitochondrial adaptation (Lin et al., 2000; Houtkooper et al., 2012). In addition to PGC-1α, SIRT1 also deacetylates forkhead box O (FOXO) transcription factors, enhancing the expression of lipid oxidation and oxidative stress protection genes (Brunet et al., 2004). Interestingly, FOXOs can also act as critical regulators of mitochondrial homeostasis through, at least, two additional means: (i) by regulating the expression of Mul1, a mitochondrial...
E3 ubiquitin ligase that controls Mfn2 degradation rates (Lokireddy et al., 2009), and (ii) by regulating the expression of the PTEN-induced kinase 1 (PINK1), a key component of the mitophagy machinery (Mei et al., 2009). This intricate transcriptional network constitutes an excellent mechanism to fine-tune oxidative metabolism and longer-term adaptations.

**Regulation of mitochondrial metabolism upon nutrient scarcity**

**Acute regulation** Nutrient scarcity in organisms is linked to an increase in circulating glucagon and other stress hormones, such as norepinephrine, which generally increase intracellular cAMP levels and PKA signaling (Fig 2A). Under these circumstances, mitochondrial fission is typically observed (Liesa & Shirihai, 2013) (Fig 2A). Elongated mitochondria upon fasting possess more cristae and increased levels of dimerization and activity of ATP synthase, ensuring a better coupling of fuel oxidation with ATP synthesis (Gomes et al., 2011). These changes in mitochondrial cristae content could also contribute to an optimal assembly of so-called respiratory supercomplexes, promoting a more efficient electron flux through the respiratory chain (Cogliati et al., 2013). On the other hand, mitochondria that fail to elongate are degraded by mitophagy. As a consequence, the transcriptional regulators that are subject to SIRT3 deacetylation are attenuated. This is further emphasized by the activation of steroid receptor coactivator protein 1 (SRC1) and the acetyltransferase GCN5. (C) During high-fat diet feeding, the nuclear receptor corepressor 1 (NCoR1) is upregulated and thereby represses the activity of key transcription factors that modulate mitochondrial activity, such as nuclear respiratory factor 1 (NRF1), NRF2, and estrogen-related receptors (ERRs), as well as peroxisome proliferator-activated receptors (PPARs).

![Figure 3](image-url)
energy stress is the AMP-activated protein kinase (AMPK), an enzyme that is activated by increases in the AMP/ATP ratio (Fig 2B). Upon activation, AMPK activates catabolic pathways and switches off energy-consuming processes. One of these targets is PGC-1α (Jager et al., 2007). Upon phosphorylation, PGC-1α is recognized as a deacetylation target by SIRT1 (Canto & Auwerx, 2009; Iwabu et al., 2010). As a consequence, PGC-1α coactivates a set of transcription factors involved in mitochondrial metabolism, including estrogen-related receptors, nuclear respiratory factors, and PPARs (Andreux et al., 2013). This two-step activation of PGC-1α might be a conserved mechanism for AMPK to confer specificity among the various targets of SIRT1 (Canto & Auwerx, 2010). Other effectors of AMPK are the FOXO transcription factors (Greer et al., 2007), which are also a target for deacetylation by SIRT1 (Brunet et al., 2004). The deacetylated FOXO will then contribute to the regulation of mitochondrial function and lipid metabolism (Canto & Auwerx, 2009). A second connection between fasting-induced transcriptional adaptation and mitochondrial dynamics lies in the transcriptional regulation exerted by fasting-related hormones. So far, however, this has been a largely unexplored territory. For example, dexamethasone induces Drp1 expression in liver cells and thereby changes mitochondrial morphology and metabolism that favor gluconeogenic procedures (Hernandez-Alvarez et al., 2013). To what extent these pathways are also active in other tissues and in other physiological conditions needs to be determined.

Additional interest on how nutrient scarcity modulates mitochondrial function comes from the fact that CR is the most consistent physiological intervention to improve health and extend lifespan across a wide range of organisms (Fontana et al., 2010; Houtkooper et al., 2010b). The relationship between CR and mitochondrial regulation is, however, still under debate. Initial evidence indicated that CR enhances mitochondrial content (Nisoli et al., 2005). These findings were rapidly accepted and have led to the concept that CR induces mitochondrial biogenesis, even though some studies found no increase in mitochondrial protein content upon CR (Hancock et al., 2008). Interestingly, a recent report indicates that CR enhances mitochondrial function without changes in mitochondrial content or biogenesis (Lanza et al., 2012). The mechanisms underlying this enhanced function are, however, not clear. A conciliatory hypothesis would be that CR protects against mitochondrial dysfunction by improving mitochondrial dynamics and the efficiency of mitophagic processes.

The role of mitochondria in caloric excess

Acute regulation Lipid overloading promotes fast and transient changes in mitochondrial architecture. Studies in Zucker rats and obese humans have shown that Mfn2 was strongly decreased in their skeletal muscle tissues compared to the control groups, which was associated with smaller mitochondrial network and size (Bach et al., 2003). Along with this fusion deficiency, mitochondrial fission is induced within minutes after a lipid overload in INS-1 cells (Molina et al., 2009; Liesa & Shirihai, 2013) (Fig 3A). Additional recent efforts have elegantly demonstrated that lipid overload also enhances norepinephrine-induced mitochondrial fission in brown adipocytes in vivo and ex vivo (Wikstrom et al., 2014). These mitochondrial fission events promoted mitochondrial uncoupled respiration (Liesa & Shirihai, 2013; Wikstrom et al., 2014). A key issue that requires further study is the basic mechanism by which fission enhances mitochondrial uncoupling. In this sense, evaluating whether fission alters cristae structure and supercomplex assembly will be interesting in the future. Irrespective of the mechanism, mitochondrial uncoupling upon lipid loading may be a way to dissipate energy and prevent detrimental lipid deposition in the cell (Liesa & Shirihai, 2013). In line with the above observations, obese patients display a largely fragmented mitochondrial network in skeletal muscle (Bach et al., 2003). The analysis of mice with mitochondrial fission or fission defects will be key to evaluate the relevance of fusion/fission in the acute adaptation to nutrient challenges.

Considering that global deletion of key mitochondrial dynamics proteins, such as Mfn1, Mfn2, Opa1 or Drp1, leads to embryonic lethality (Chen et al., 2003; Davies et al., 2007; Ishihara et al., 2009), tissue-specific knockout models are currently being explored. Indeed, deletion of Mfn2 in the liver disrupts mitochondria-ER connectivity and thereby induces ER stress-mediated susceptibility to metabolic disease upon high-fat feeding (Sebastian et al., 2012), indicating once more that the regulation of mitochondrial dynamics is essential to meet metabolic challenges. Defective mitochondrial dynamics and mitochondrial-ER communication in hypothalamic POMC and AgRP neurons might actually modify feeding behavior and whole-body energy homeostasis (Dietrich et al., 2013; Schneebaumer et al., 2013).

Dietary excess of lipids also dramatically changes mitochondrial protein acetylation. One week of HFD enhanced SIRT3 levels and prevented mitochondrial hyperacetylation despite the higher levels of lipid substrates (Hirschey et al., 2010). This increase in SIRT3 may represent a cellular adaptation to cope with the need to use fatty acid oxidation as the main path for energy production. Conversely, prolonged HFD dramatically decreases SIRT3 expression, correlating with the appearance of mitochondrial hyperacetylation and mitochondrial dysfunction (Hirschey et al., 2010). To date, it is still unclear why the initial adaptations tend to disappear with time, ultimately driving the organism into metabolic disease.

Transcriptional responses Changes in mitochondrial dynamics are apparent in the acute phase of caloric excess. Still, however, Mfn2 expression is also reduced, possibly through transcriptional regulation. Similar to many mitochondrial genes, Mfn2 expression is controlled by PGC-1α (Soriano et al., 2006), suggesting that decreased PGC-1α activity explains the defects in Mfn2 observed in obese and T2DM individuals. Indeed, HFD in mice leads to hyperacetylated, inactive, PGC-1α (Coste et al., 2008). This is likely regulated at several levels. During HFD, SIRT1 expression is reduced, while the GCN5 acetyltransferase, which acetylates PGC-1α, is expressed at higher levels (Coste et al., 2008). HFD also reduces the NAD⁺ content in diverse tissues, which is likely to impair SIRT1 activation (Kim et al., 2011; Yoshino et al., 2011) (Fig 3B). The resulting hyperacetylation of PGC-1α renders it unable to properly coactivate target transcription factors, leading to decreased mitochondrial biogenesis.

The expression of repressive transcriptional regulators, such as the nuclear receptor corepressor 1 (NCoR1), is also enhanced by HFD, repressing genes that control mitochondrial activity and contributing to the excessive calorie storage (Yamamoto et al., 2011) (Fig 3C). In fact, PGC-1α and NCoR1 oppositely regulate several transcription factors, including nuclear respiratory factors, estrogen-related receptors...
Higher flux of lipid substrates (Garcia-Roves et al., 2007; Hancock et al., 2008). However, prolonged lipid overload compromises mitochondrial function. The threshold for this to happen and the reason behind it still need to be solved, but it seems likely that this defective mitochondrial function can dramatically change through fusion/fission events. Indeed, higher mitochondrial protein content, but to the ability to adapt mitochondrial activity and biogenesis to external stimuli. Indeed, higher mitochondrial content could also be due to deficiencies in mitochondrial recycling mechanisms and in fact be linked to mitochondrial dysfunction. This is the case, for example, in muscle-specific AMPK knockouts, which display enlarged but dysfunctional mitochondria (O’Neill et al., 2011).

In light of the evidence reviewed here, the evaluation of mitochondrial content as a readout for function might lead to contrive observations on the relationship between diverse pathologies, lipid oxidation rates, and true mitochondrial function. This advocates for the need to determine various additional aspects of mitochondrial well-being to certify changes in mitochondrial function within pathophysiological states. Still, some key questions remain unanswered, such as (i) why does mitochondrial content decline upon a certain length of fat overfeeding and how can this be prevented, and (ii) can strategies aimed to enhance insulin sensitivity be successful without proper mitochondrial fitness? Needless to say, interesting times lie ahead.

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Conflict of interest
CC is an employee of the Nestlé Institute of Health Sciences. All other authors declare that they have no conflict of interest.

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