AMP-activated protein kinase (AMPK) is an energy sensor that regulates cellular metabolism. When activated by a deficit in nutrient status, AMPK stimulates glucose uptake and lipid oxidation to produce energy, while turning off energy-consuming processes including glucose and lipid production to restore energy balance. AMPK controls whole-body glucose homeostasis by regulating metabolism in multiple peripheral tissues, such as skeletal muscle, liver, adipose tissues, and pancreatic β cells — key tissues in the pathogenesis of type 2 diabetes. By responding to diverse hormonal signals including leptin and adiponectin, AMPK serves as an intertissue signal integrator among peripheral tissues, as well as the hypothalamus, in the control of whole-body energy balance.

Nonstandard abbreviations used: ACC, acetyl-CoA carboxylase; AICAR, 5-aminoimidazole-4-carboxamide riboside; AMPK, AMP-activated protein kinase; AS160, Akt substrate of 160 kDa; CaMKK, calmodulin-dependent protein kinase kinase; CREB, cAMP response element-binding protein; GLUT4, glucose transporter 4; PEPCK, phosphoenolpyruvate carbox kinase; PGC-1, PPARγ coactivator 1; T2D, type 2 diabetes; TORC2, transducer of regulated CREB activity 2.

Conflict of interest: The laboratory of J.R. Zierath receives research funding from Arexis AB, Sweden, which investigates pharmaceutical targeting of AMPK.

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activators of AMPK such as hyperosmotic stress do not appear to alter this ratio (12), suggesting that other mechanisms are involved in the regulation of the AMPK pathway.

**AMPK regulates metabolism in peripheral tissues**

*Role of AMPK in exercise-induced glucose uptake in skeletal muscle.* Skeletal muscle is the major site of insulin-stimulated glucose disposal (16), and insulin resistance in this target tissue has long been viewed as a contributing factor in the pathogenesis of T2D. Therefore, alternative pathways that stimulate skeletal muscle glucose uptake independently of insulin signaling could potentially improve glycemic control in T2D subjects. Although exercise stimulates glucose uptake in skeletal muscle independently of the insulin pathway, the underlying molecular mechanism remains largely elusive.

The finding that glucose transport can be increased in isolated skeletal muscle in response to contraction in vitro suggests that the signaling pathways elicited by internal cellular energy deficiency are partly accountable for contraction-induced glucose uptake. AMPK is considered as an attractive candidate for contraction-induced skeletal muscle glucose uptake because it is activated in parallel with elevation in AMP and a reduction in creatine phosphate energetic stores (17). Furthermore, AICAR-induced activation of AMPK increases glucose uptake (18), concomitantly with glucose transporter 4 (GLUT4) fusion with plasma membrane (19). The AICAR effect on glucose uptake is not affected by inhibition of the insulin-dependent PI3K pathway and is additive to insulin-stimulated glucose uptake, reminiscent of the exercise effect. However, in rat slow-twitch (oxidative) soleus muscle, AICAR does not induce glucose uptake, although phosphorylation of AMPK is increased (20). Furthermore, in slow-twitch muscle, contraction induces glucose uptake without any apparent increase in AMPK activity when there is a high glycogen content. (21). Given that AICAR induces AMPK phosphorylation and glucose uptake in rat fast-twitch (glycolytic) epitrochlearis muscle, the role of AMPK in mediating muscle glucose uptake is likely to be dependent on fiber type.

Earlier studies linking AMPK signaling with glucose metabolism were correlative in nature. The introduction of transgenic and genetic knockout mouse models to study AMPK action has enhanced our understanding of AMPK signaling in contraction-induced glucose uptake (Table 1). Overexpression of an α2 kinase–dead subunit in skeletal muscle abolishes AICAR, but only partially impairs contraction-stimulated glucose uptake (22). Furthermore, ablation of skeletal muscle AMPK α2 and γ3 subunit expression does not affect glucose uptake stimulated by contraction, although the AICAR effect is blunted (23–25). In the skeletal muscle–specific LKB1 knockout, however, glucose uptake in response to AICAR and contraction is impaired (26). These findings suggest that additional pathways mediate contraction-induced glucose uptake.

**Figure 1**

Structure and regulation of AMPK. AMPK is a heterotrimeric complex consisting of an α, a β, and a γ subunit and is activated by the upstream kinases CaMKK and LKB1 via phosphorylation of threonine residue 172. Activation of AMPK by CaMKK and LKB1 is dependent on the intracellular calcium and AMP/ATP ratio, respectively. Generally, AMPK restores energy balance by activating processes that produce energy (e.g., lipid oxidation and glucose uptake) while inhibiting those that consume energy (e.g., protein synthesis).
fers long-chain acyl-CoA into the mitochondria, and this process is inhibited allosterically by malonyl-CoA (35), synthesized by acetyl-CoA carboxylase (ACC) (36). The activity of ACC is regulated by reversible phosphorylation, and AMPK directly phosphorylates and inactivates this downstream target (37, 38). During exercise (37) and skeletal muscle contraction (17), activated AMPK inhibits ACC to reduce malonyl-CoA concentration, thereby driving the entry of long-chain acyl-CoA into the mitochondria for β-oxidation to restore energy balance (18, 39). The ability of AMPK to induce lipid oxidation and thus lower skeletal muscle (40) and liver (33) lipid deposition is considered an important feature for the insulin-sensitizing effect of AMPK activation. Indeed, when an activating form of AMPK γ3(R225Q) subunit is expressed in skeletal muscle via genetic manipulation, the transgenic mice are protected against the development of diet-induced skeletal muscle insulin resistance (25). This effect is associated with lower skeletal muscle triglyceride stores as a result of increased fatty acid oxidation (25).

AMPK activation, mitochondrial biogenesis, and insulin sensitivity in skeletal muscle. Exercise has been long recognized as an essential element of clinical management of T2D. Long-term exercise training enhances insulin sensitivity and glucose uptake in skeletal muscle (41, 42) and promotes mitochondrial biogenesis, which leads to improved oxidative metabolism (43). Decreased mitochondrial density and activity have been proposed to partly account for the development of skeletal muscle insulin resistance (44–46). Given that activation of AMPK recapitulates some of the exercise-induced adaptations, it is likely to mediate some beneficial effects of exercise on glucose homeostasis (41, 42).

Activation of AMPK by hypoxia and AICAR mimics contraction-enhanced insulin sensitivity of glucose transport in isolated skeletal muscle (47). In long-term treatment studies, in vivo AICAR administration increases GLUT4 and hexokinase II expression (48, 49) and enhances insulin-stimulated muscle glucose transport (50, 51) and GLUT4 translocation (51). In genetic mouse models, an activating mutant AMPK γ3(R225Q) subunit enhanced expression of genes essential for skeletal muscle lipid and oxidative metabolism, whereas ablation of the AMPK γ3 subunit impaired the expression of these genes (52, 53). In response to exercise, mutant γ3(R225Q) mice demonstrated enhanced skeletal muscle expression of GLUT4 and hexokinase II, whereas expression of these genes during recovery was blunted in γ3 knockout mice (54). The mechanisms for such effects are unclear. Nonetheless, several studies revealed can-

### Table 1

**In vivo validation of the AMPK pathway in mouse models**

<table>
<thead>
<tr>
<th>Model</th>
<th>Description of phenotype</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skeletal and cardiac muscle–specific overexpression of AMPK</td>
<td>Abolished AICAR- and hypoxia-induced skeletal muscle glucose uptake, impaired contraction-stimulated glucose uptake</td>
<td>22</td>
</tr>
<tr>
<td>α2 dominant negative</td>
<td>Impaired skeletal muscle mitochondrial biogenesis following chronic energy deprivation Diminished glycogen content and resynthesis after exercise, skeletal muscle fiber hypertrophy</td>
<td>56 111</td>
</tr>
<tr>
<td>Total AMPK α1 knockout</td>
<td>No apparent phenotype observed</td>
<td>24</td>
</tr>
<tr>
<td>Total AMPK α2 knockout</td>
<td>Insulin resistance, impaired AICAR and glucose tolerance, impaired glucose-stimulated insulin secretion, reduced insulin-stimulated whole-body glucose utilization and skeletal muscle glycogen synthesis, elevated catecholamine excretion in urine Abolished AICAR-stimulated skeletal muscle glucose transport, reduced skeletal muscle glycogen content Increased body weight and fat mass following high-fat diet</td>
<td>110 24 76</td>
</tr>
<tr>
<td>Total AMPK γ3 knockout</td>
<td>Abolished AICAR-induced skeletal muscle glucose transport, impaired skeletal muscle glycogen resynthesis after exercise Impaired fasting-induced skeletal muscle metabolic gene expression Impaired exercise-induced skeletal muscle metabolic gene expression Susceptibility to contraction-induced muscle fatigue</td>
<td>25 52, 53 54 112</td>
</tr>
<tr>
<td>Skeletal muscle–specific overexpression of AMPK γ3</td>
<td>No apparent metabolic phenotype observed</td>
<td>25</td>
</tr>
<tr>
<td>Skeletal muscle–specific overexpression of AMPK γ3 R225Q mutant</td>
<td>Reduced skeletal muscle fat deposition and insulin resistance following a high-fat diet, increased glycogen content, impaired AICAR-stimulated glucose transport, elevated glycogen resynthesis after exercise Enhanced expression of lipid metabolic genes Enhanced exercise-induced fat utilization and gene expression, diminished exercise-induced skeletal muscle glucose oxidation Resistance to contraction-induced muscle fatigue</td>
<td>25 52, 53 54 112</td>
</tr>
<tr>
<td>Skeletal muscle–specific LKB1 deletion</td>
<td>Inhibited AICAR- and contraction-induced skeletal muscle glucose transport</td>
<td>26</td>
</tr>
<tr>
<td>Liver-specific LKB1 deletion</td>
<td>Increased hepatic gluconeogenic and lipogenic gene expression, fasting hyperglycemia, glucose intolerance, resistance to metformin treatment following a high-fat diet</td>
<td>67</td>
</tr>
<tr>
<td>Muscle-specific overexpression of AMPK α2 dominant negative</td>
<td>AICAR intolerance, impaired AICAR- and rotenone-induced skeletal muscle glucose uptake</td>
<td>23</td>
</tr>
<tr>
<td>Liver-specific AMPK α2 knockout</td>
<td>Fasting hyperglycemia, glucose intolerance, elevated hepatic glucose production, impaired leptin- and adiponectin-regulated hepatic glucose production</td>
<td>65</td>
</tr>
</tbody>
</table>
Glucagon and fasting conditions induce hepatic TORC2 nuclear translocation, which enhances CREB-dependent transcription of the gluconeogenic program, including PGC-1α. Conversely, AMPK activation causes TORC2 phosphorylation and sequesters the coactivator in the cytoplasm, thus blunting the expression of the gluconeogenic program. Deletion of hepatic LKB1 (an upstream kinase of AMPK) abolishes AMPK activation and leads to nuclear accumulation of TORC2, which in turn drives gluconeogenesis (67). Consistently, liver LKB1 knockout mice on a high-fat diet exhibit fasting hyperglycemia and glucose intolerance and are unresponsive to metformin treatment (67).

In addition to gluconeogenesis, AMPK action has been implicated in regulation of liver lipogenesis, lipid oxidation, and cholesterol synthesis (4, 6). AMPK suppresses glucose-induced expression of lipogenic-associated genes such as fatty acid synthase (33, 68), ACC, and pyruvate kinase (69). In rat primary hepatocytes, activation of AMPK by AICAR or metformin increases fatty acid oxidation via inhibition of ACC (33). Consistently, in rats treated with metformin, triglyceride levels are reduced, concomitantly with an increase in β-hydroxybutyrate, suggesting elevated hepatic lipid oxidation (33). These enhanced metabolic profiles are accompanied by downregulation of lipogenic genes such as SREBP-1, fatty acid synthase, and S14 (33). Moreover, the lipid-lowering effects of metformin in cultured hepatocytes require AMPK activity (70). Taken together, the studies provide evidence that AMPK suppresses liver gluconeogenesis and lipid production, while decreasing hepatic lipid deposition via increased lipid oxidation, thus improving the glucose and lipid profile in T2D.

AMPK regulates lipid metabolism in adipocytes. A common characteristic of T2D is high circulating lipid levels of lipids, partly accounted for by impaired insulin-mediated suppression of lipolysis
in adipose tissue (62, 71). Elevated circulating FFAs released by adipocytes are associated with ectopic fat accumulation and can cause insulin resistance in skeletal muscle and liver, as well as impaired insulin secretion by β cells (72). Insulin controls the release of FFAs from adipose tissue by inhibition of hormone-sensitive lipase, a rate-limiting enzyme of lipolysis. However, AMPK has also been implicated in the regulation of lipolysis through direct phosphorylation of hormone-sensitive lipase, which leads to inhibition of subsequent activation by protein kinase A (73). AMPK is thought to inhibit lipolysis, since treatment of isolated rat adipocytes with AICAR antagonizes isoprenaline-induced lipolysis (13, 74). Furthermore, expression of a constitutively active form of AMPK reduces isoproterenol-stimulated lipolysis, whereas reduced AMPK activity increases lipolysis in adipocytes (75). AMPK inhibits lipogenesis in isolated adipocytes via increased ACC phosphorylation in response to AICAR stimulation (74). AMPK also appears to control whole-body adiposity; when subjected to a high-fat diet, AMPK α2 knockout mice developed increased body weight and fat mass as compared with the wild-type mice (76). Although an in vivo antilipolytic effect of AICAR has been demonstrated (77), AMPK activity in adipocytes is paradoxically augmented in response to fasting (75), a condition when lipolysis is elevated. Furthermore, there is also evidence that activation of AMPK promotes lipolysis (78). Therefore, the physiological relevance and role of AMPK in the regulation of lipolysis in vivo remain to be addressed.

**AMPK and insulin release by pancreatic β cells.** The SNF1 complex (a yeast ortholog of AMPK) in *S. cerevisiae* responds to changes in the glucose concentration in the medium and is essential for transcriptional activation of glucose-repressed genes (3–5). This glucose-sensing property is also found in mammalian pancreatic β cells. Glucose increases the intracellular ATP/ADP ratio in β cells (79, 80), which induces closure of ATP-sensitive potassium channels (81), and influx of calcium ions (82), a critical step in exocytosis of insulin (83). Moreover, AMP and ADP concentrations in β cells decrease in response to elevations in glucose concentration (84, 85), and this suggests that AMPK could play a role in insulin release by acting as a fuel sensor. An increase in glucose levels represses AMPK activity in β cell lines (85–88), whereas AICAR-induced activation of AMPK markedly reduced glucose-stimulated insulin release from primary pancreatic islets (85, 87) and β cell lines (87, 89). Furthermore, overexpression of a constitutively active form of AMPK reduces calcium influx in response to depolarizing agents and results in repressed glucose-induced insulin release from β cell lines (87, 90). Conversely, overexpression of a dominant-negative form of AMPK leads to increases in insulin release without apparent changes in glucose metabolism and calcium influx (87). Despite its profound effect on insulin release, the role of AMPK in β cell vesicle trafficking is unclear, and downstream targets of AMPK that mediate these physiological processes remain to be identified.

Given that antidiabetic drugs such as metformin activate AMPK, AMPK activators have been proposed to counter effects on insulin release in T2D patients (91). Incubation of either human islets or cultured β cells with metformin activates AMPK and inhibits glucose-stimulated insulin secretion (88). Although seemingly undesirable in the treatment of T2D, AMPK-mediated suppression of insulin release may be physiologically relevant for maintaining glucose homeostasis through inhibition of insulin secretion during glucose deficiency. The role of AMPK in the regulation of β cell function is clearly an unresolved question that requires further investigation.

### Integration of intertissue signaling by AMPK

**Leptin.** One of the central roles of AMPK in the regulation of whole-body glucose homeostasis is to integrate hormonal and nutrient signals in multiple tissues (Figure 3). Leptin is an adipocyte-derived hormone that diminishes adiposity by reducing food intake (92) and improves insulin sensitivity (93), at least in part by depleting triglyceride stores in peripheral tissues (94, 95). In peripheral tissues, leptin induces fatty acid oxidation (96) and...
Review series

Glucose uptake (97, 98), 2 metabolic responses that are also triggered by AMPK activation; this implicates AMPK kinase as a candidate in the mediation of leptin responses. Intravenous injection of leptin was found to induce fatty acid oxidation via inhibition of ACC and activate AMPK α2 in skeletal muscle in a biphasic manner (99). An early and transient activation of AMPK in skeletal muscle occurred as a direct response to leptin treatment via an increase in the AMP concentration. A later, more sustained activation was mediated by hypothalamic–sympathetic nervous system and skeletal muscle α-adrenergic receptors without any apparent change in AMP level (99).

Adiponectin. Adiponectin is another adipokine that lowers plasma glucose and FFAs in mice challenged with a high-fat diet (100). These effects are partly accounted for by adiponectin-induced AMPK activation, which in turn stimulates skeletal muscle fatty acid oxidation and glucose uptake (101, 102). Furthermore, activation of AMPK by adiponectin suppresses endogenous glucose production, concomitantly with inhibition of PEPCK and G6Pase expression (102). The AMPK pathway mediates metabolic effects of adipocyte-derived adiponectin in skeletal muscle and liver, thereby integrating communication among the 3 organs.

Role of AMPK in energy homeostasis. The hypothalamus plays a key role in whole-body energy homeostasis by regulating peripheral metabolism (103, 104) and food intake (103–105) in response to hormones and nutrients. AMPK acts as a fuel sensor in the hypothalamus and responds to a variety of metabolic and nutrient factors. Injection of leptin and insulin (anorexigen) (106, 107) into rodents inhibits AMPK activity in the hypothalamus; conversely, administration of orexigenic peptides including ghrelin (106) and agouti-related protein (107) increases AMPK activity. The modulation of hypothalamic AMPK in rodents alters food intake: activation of AMPK by AICAR and α-lipoic acid in the hypothalamus increases food intake (106, 108), whereas anorexigenic and weight-reducing effects of leptin are attenuated when constitutively active AMPK is expressed in the hypothalamus (107). Apart from signals elicited by biological peptides, a decrease in fuel availability such as under fasting conditions (107, 108) activates hypothalamic AMPK activity. In contrast, hyperglycemia and refeeding inhibit AMPK activity in the hypothalamus (107).

Apart from the effects on food intake, additional roles of hypothalamic AMPK in the central control of peripheral metabolism are likely. The hypothalamic–sympathetic nervous system axis partly mediates leptin-induced skeletal muscle fatty acid oxidation (99). Intracerebroventricular administration of AICAR activates hypothalamic AMPK and triggers increased glycogen synthesis in skeletal muscle (109). Furthermore, total AMPK α2 knockout mice display impaired insulin-stimulated whole-body glucose utilization and skeletal muscle glycogen synthesis, although underlying mechanisms are unknown (99, 110). Therefore, further studies are critical for understanding the role of hypothalamic AMPK in the regulation of whole-body metabolism.

Conclusion

AMPK represents a diverse, yet versatile energy sensor and metabolic regulator that exerts a regulatory effect in the hypothalamus and multiple peripheral tissues. Activation of AMPK in skeletal muscle, liver, and adipose tissue enhances metabolism, insulin sensitivity, and gene expression to collectively promote a favorable metabolic milieu for the prevention or treatment of T2D. However, activated AMPK can induce food intake through its action in the hypothalamus. This effect is probably a physiological response for glucose homeostasis but will likely be undesirable for pharmacological targeting of AMPK for the treatment of T2D and obesity. Therefore, tissue-specific pharmacological activation of AMPK is essential and could potentially be achieved through isoform-specific activation or targeting of downstream substrates of AMPK. Given that many AMPK-regulated metabolic pathways are also controlled by other hormonal and metabolic signals, elucidation of the cross-talk between these pathways is also essential. Moreover, research into the AMPK system provides compelling molecular support for adopting exercise in the prevention and treatment of T2D. This of course does not disparage the need for pharmaceutical targeting of the AMPK pathway for a multimodal approach in the prevention and treatment of T2D.

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Address correspondence to: Juleen R. Zierath, Karolinska Institutet, Department of Molecular Medicine and Surgery, Section of Integrative Physiology, von Euler's väg 4, 4th Floor, S-171 77 Stockholm, Sweden. Phone: 46-8-524-875-80; Fax: 46-8-33-54-36; E-mail: Juleen.Zierath@ki.se.

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