OPEN

Experimental & Molecular Medicine (2016) 48, e224; doi:10.1038/emm.2016.16

www.nature.com/emm

REVIEW

AMPK activators: mechanisms of action and physiological activities

Joungmok Kim[1], Goowon Yang[2], Yeji Kim[2], Jin Kim[2] and Joohun Ha[3]

AMP-activated protein kinase (AMPK) is a central regulator of energy homeostasis, which coordinates metabolic pathways and thus balances nutrient supply with energy demand. Because of the favorable physiological outcomes of AMPK activation on metabolism, AMPK has been considered to be an important therapeutic target for controlling human diseases including metabolic syndrome and cancer. Thus, activators of AMPK may have potential as novel therapeutics for these diseases. In this review, we provide a comprehensive summary of both indirect and direct AMPK activators and their modes of action in relation to the structure of AMPK. We discuss the functional differences among isoform-specific AMPK complexes and their significance regarding the development of novel AMPK activators and the potential for combining different AMPK activators in the treatment of human disease.

Experimental & Molecular Medicine (2016) **48,** e224; doi:10.1038/emm.2016.16; published online 1 April 2016

INTRODUCTION

As a cellular energy sensor, AMP-activated protein kinase (AMPK) is activated in response to a variety of conditions that deplete cellular energy levels, such as nutrient starvation (especially glucose), hypoxia and exposure to toxins that inhibit the mitochondrial respiratory chain complex.[1,2] AMPK is a serine/threonine protein kinase complex consisting of a catalytic α-subunit (α1 and α2), a scaffolding β-subunit (β1 and β2) and a regulatory γ-subunit (γ1, γ2 and γ3; Figure 1). Ubiquitous expression of AMPKα1-, β1- and γ1-subunits in many tissues makes the α1β1γ1 complex a reference for AMPK assays to identify AMPK activators. However, given the unique functions and/or subcellular (or tissue)-specific distribution of the distinct AMPK complex,[3–5] referencing screening to the α1β1γ1 complex may present a limited range of the physiology of AMPK. In line with this notion, increasing evidence shows that inactivating mutations and genetic deletion of specific isoforms produce tissue-specific physiological results.[6–8] Mutations in the AMPKγ2 subunit have frequently been observed in human cardiomyopathies, and deletion of the AMPKα2 subunit, but not α1, has been shown to decrease infarct volume in mouse models of stroke.

Allosteric activation of AMPK by AMP

The first class of direct AMPK activators is small molecules that mimic cellular AMP. These molecules trigger a conformational change in the AMPK complex that allows further activation by phosphorylation of Thr-172 in the AMPKα subunit.[9,10] The molecular mechanism underlying allosteric activation of AMPK by AMP binding has been demonstrated by several recent studies of the three-dimensional structure of AMPK.[11–13] This crystal structure has shown the importance of cystathionine-β-synthase domain repeats within the AMPKγ subunit in the molecular mechanism by which AMPK is activated in response to cellular adenosine nucleotides (AMP, ADP or ATP). Four consecutive cystathionine-β-synthase domains in the AMPKγ subunit provide four potential adenine nucleotide-binding sites. These sites are numbered Sites 1–4, according to the number of the cystathionine-β-synthase domain repeat carrying a conserved aspartate residue involved in ligand binding.[11,14,15] In the mammalian AMPKγ1 subunit, Site 2 appears to be always empty and Site 4 to have a tightly bound AMP molecule, whereas Sites 1 and 3 represent the regulatory sites that bind AMP, ADP or ATP, which compete for binding.[16] AMP binding to Site 1 appears to cause allosteric activation, whereas binding of AMP or ADP to Site 3 appears to modulate the phosphorylation state of Thr172.[13] Although cellular ADP levels are higher than those of AMP, a recent study has shown that AMP is a bona fide activator that enhances LKB1-dependent Thr 172 phosphorylation *in vivo*.[17] AMP binding to the AMPKγ subunit serves as an important regulatory feature of the conformational switch that activates

---

[1]Depatment of Oral Biochemistry and Molecular Biology, School of Dentistry, Kyung Hee University, Seoul, Korea; [2]Department of Biomedical Science, Graduate School, Kyung Hee University, Seoul, Korea and [3]Department of Biochemistry and Molecular Biology, Graduate School, Kyung Hee University, Seoul, Korea

Correspondence: Professor J Ha, Department of Biochemistry and Molecular Biology, Graduate School, Kyung Hee University, 26, Kyungheedae-ro, Dongdaemun-gu, Seoul 02447, Korea.

E-mail: hajh@khu.ac.kr

Received 1 December 2015; revised 28 December 2015; accepted 29 December 2015

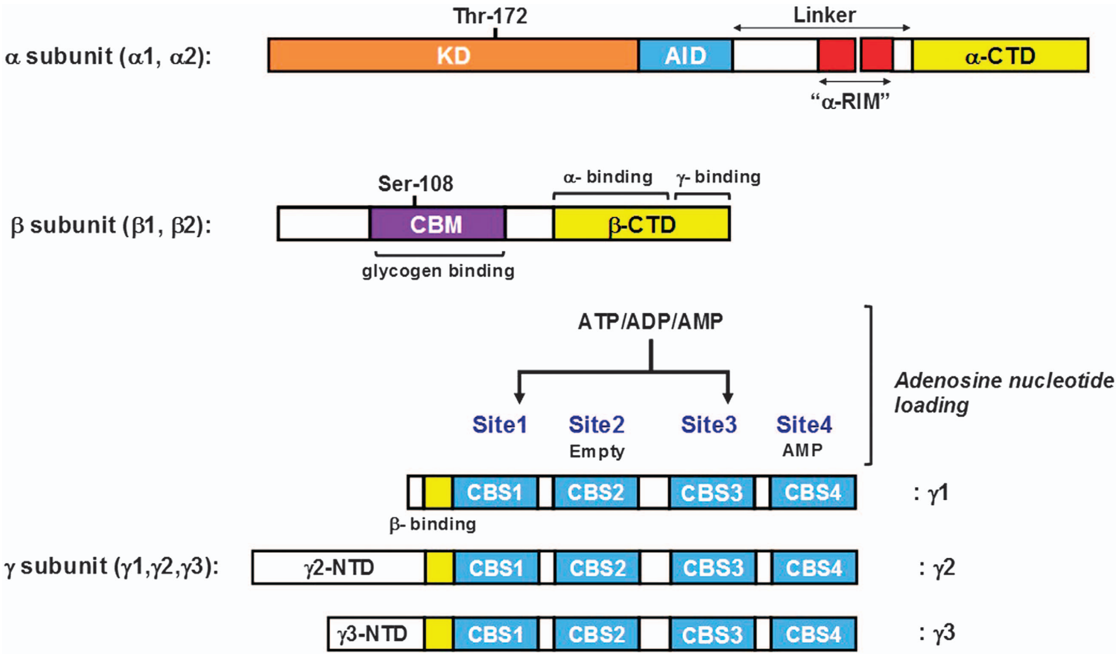


Figure 1 Functional domains of AMP-activated protein kinase (AMPK) subunits. The mammalian α1/α2 and β1/β2 isoforms are very similar, and their characteristic features are shown. AMPKα subunits: KD, kinase domain containing Thr-172 for the activation by upstream kinases; AID, autoinhibitory domain; two α-RIM, regulatory subunit interacting motifs triggering the conformational changes in response to AMP binding to the AMPKγ subunit; α-CTD, C-terminal domain binding to the β-subunit. AMPKβ subunit: CBM, carbohydrate-binding module, in which Ser108 is important for the action of some direct AMPK activators, such as thienopyridone (A-769662) and salicylate; β-CTD, C-terminal domain containing α-subunit-binding site and immediately followed by the domain for γ-subunit interaction. AMPKγ subunit: three γ-subunit isoforms have variable N-terminal domains (NTDs); four CBS, cystathione-β-synthases domain, which forms two Bateman domains that create four adenosine nucleotide-binding sites (Sites 1–4). Site 2 appears to be always empty and Site 4 to have a tightly bound AMP, whereas Sites 1 and 3 represent the regulatory sites that bind AMP, ADP or ATP in competition.

the AMPK complex. The catalytic AMPKα subunit contains an N-terminal kinase domain (KD) immediately followed by an autoinhibitory domain (AID). The three-dimensional structure shows that the AID interacts with the small and large lobes of the KD and causes AMPK to be maintained in an inactive conformation. Once AMP binds to the AMPKγ subunit, the α-RIM (regulatory subunit-interacting motif) between the KD/AID and a globular C-terminal domain of the AMPKα subunit interact with one of the regulatory adenosine nucleotides on the AMPKγ subunit in a manner akin to two arms wrapping around the adenosine. These conformation changes release and expose the KD of AMPKα from its AID to activate the AMPK complex.

Regulation of AMPK activity by upstream kinases

Physiological AMPK activation involves phosphorylation of Thr-172 within the activation loop of the KD in the AMPKα catalytic subunit. Two upstream kinases, LKB1[18] and CaMKKβ (Ca^{2+}/calmodulin-dependent protein kinase β),[19] have been extensively documented to phosphorylate Thr-172 of the AMPKα subunit. Notably, there are lines of evidence showing that the LKB1-dependent AMPKα phosphorylation at Thr172 is greatly enhanced by the binding of AMP to the AMPK γ-subunit, and, at the same time, the AMP-binding inhibits dephosphorylation of this activating phosphorylation by protein phosphatases, such as PP2A and PP2C *in vitro*.[20,21] Interestingly, the effect of AMP on Thr172 phosphorylation of the AMPK α-subunit appears to be dependent on N-terminal myristoylation of the β-subunit, although the underlying mechanism remains to be demonstrated.[22] In contrast to the LKB1 complex, another upstream AMPK kinase, CaMKKβ, can activate AMPK in response to increases in cellular Ca^{2+} without any significant change in ATP/ADP/AMP levels. Treatments that deplete cellular ATP do not effectively activate AMPK in LKB1-negative tumors because the basal activity of CaMKKβ is too low to affect the phosphorylation status of AMPKα Thr172, although the increase in AMP due to ATP depletion makes the AMPK α-subunit a better substrate for CaMKKβ. However, these treatments can cause AMPK activation under conditions that elevate intracellular Ca^{2+}. These data indicate that the phosphorylation/dephosphorylation equilibrium at Thr-172 on the AMPK α-subunit involves AMP binding to the AMPKγ subunit and N-terminal modification of the AMPK β-subunit, adding another a level of complexity to the AMPK activation mechanism.

Physiological functions of AMPK

As its name suggests, AMPK has a key role in maintaining the balance between anabolic and catabolic programs for cellular homeostasis in response to metabolic stress.[23–28] Given the functional attributes of AMPK in glucose/lipid homeostasis, body weight, food intake, insulin signaling and mitochondrial

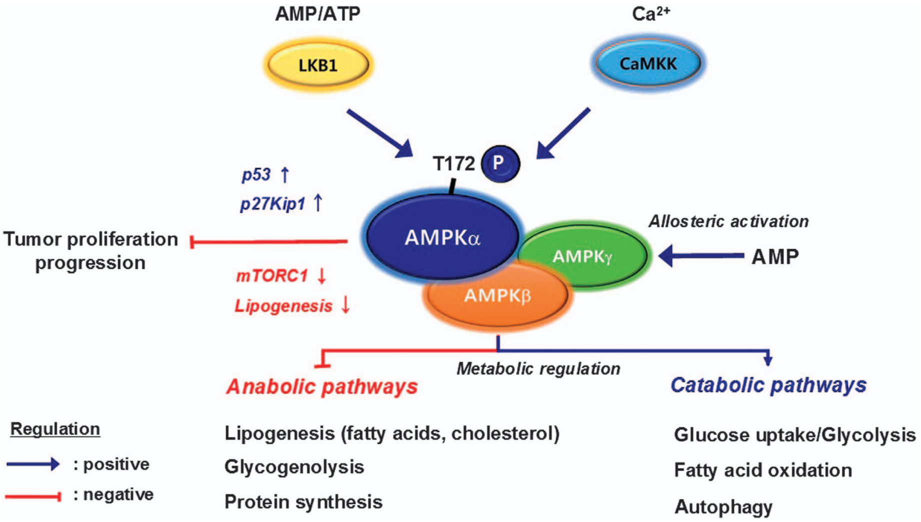


Figure 2 A summary of the physiological roles of AMP-activated protein kinase (AMPK).

biogenesis, AMPK is considered to be a major therapeutic target for the treatment of metabolic diseases including type 2 diabetes and obesity.[29,30]

A number of studies have shed light on the role of AMPK in tumorigenesis.[31] An initial report connecting AMPK to cancer biology described the discovery of the tumor suppressor LKB1 as a major AMPK upstream kinase.[32] Genetic mutations of the *LKB1* gene are responsible for inherited Peutz-Jeghers syndrome, which is characterized by the development of hamartomatous polyps in the intestine.[33] Since then, a number of *in vitro* and *in vivo* studies have suggested that AMPK indeed mediates the tumor-suppressor effects of LKB1. This is supported by findings that drugs that are capable of activating AMPK (metformin, phenformin, A-769662) delay the onset of tumorigenesis in *in vivo* models.[34,35] Much effort has been made to understand the molecular mechanisms underlying the antitumorigenic functions of AMPK. These studies have shown that mTORC1[36,37] and RNA polymerase I transcription factor TIF-1A,[38] both of which are required for rapidly proliferating cells, are under the control of AMPK. In addition, AMPK activation has been shown to cause G1 cell cycle arrest, which is associated with activation of p53, followed by induction of the cell cycle inhibitor protein, p21.[39,40] Similarly, AMPK has been shown to cause cell cycle arrest by inducing the phosphorylation and concomitant stabilization of the cyclin-dependent kinase inhibitor $p27^{kip1}$ in response to metabolic stress.[41] A recent study has described an additional layer of p53–AMPK–mTORC1 regulation via the p53-repsonsive gene products Sestrin1/2.[42] However, it should be noted that AMPK might protect tumor cells against the action of cytotoxic agents, nutrient limitation and hypoxia, once the tumors are established. Therefore, AMPK activators might be deleterious in the treatment of cancer.

Another important aspect of AMPK biology is the role of AMPK in autophagy, a lysosome-dependent catabolic program that maintains cellular homeostasis.[43–46] A number of studies have demonstrated that AMPK has important roles in autophagy regulation by directly phosphorylating two autophagy-initiating regulators: a protein kinase complex ULK1 (Unc-51-like autophagy-activating kinase)[47,48] and a lipid kinase complex PI3KC3/VPS34 (phosphatidylinositol 3-kinase, catalytic subunit type 3; also known as VPS34).[49] A number of reports have demonstrated the metabolic significance of autophagy in glycogenolysis (glycophagy)[50] and lipolysis (lipophagy)[51] and even in regulating adipose mass as well as differentiation *in vivo*.[52] In this regard, elucidating the molecular connection between AMPK and autophagy will provide a novel avenue to expand the functional network of AMPK in cellular homeostasis, including metabolism.

Given these functional attributes, as summarized in Figure 2, much effort has been made to develop robust AMPK assays and to identify AMPK modulators to provide therapies for a variety of human diseases.[53–56] In this review, we present a comprehensive summary of both indirect and direct AMPK activators and their modes of action in relation to the structure of AMPK, and discuss the implications of AMPK as a therapeutic target.

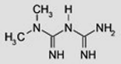
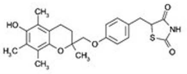
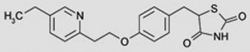
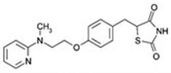
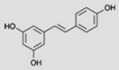
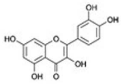
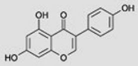
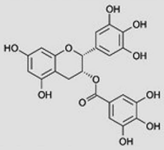
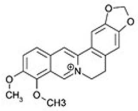
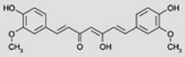
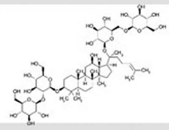
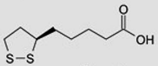
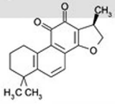
INDIRECT AMPK ACTIVATORS

Practically, AMPK can be activated by any modulator that causes AMP or calcium accumulation. These are classified as indirect activators because a direct interaction between AMPK and modulators is not necessary. Indirect AMPK activators are listed on Table 1.

Biguanides

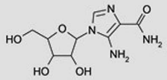
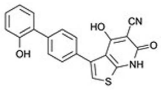
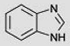
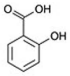
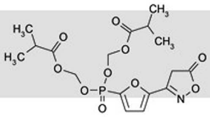
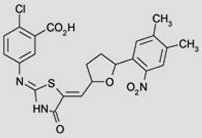
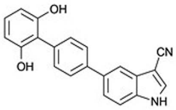
Metformin is a type of biguanide, a synthetic derivative of guanide that is a natural product from the plant *Galega officinalis*, and has been used as a first-line antidiabetic drug because of its ability to reduce hepatic glucose production and enhance peripheral insulin sensitivity.[57] A number of studies have demonstrated that the actions of metformin are

Table 1 Indirect AMPK activators

Compound name	*Chemical structure*	*Activation mechanism*	*Molecular target*	*reference*
Metformin		increase of AMP:ATP ratio	Complex I of the mitochondrial respiratory chain	58-62
Troglitazone		increase of AMP:ATP ratio	Complex I of the mitochondrial respiratory chain	63-65
Pioglitazone		increase of AMP:ATP ratio	Complex I of the mitochondrial respiratory chain	63-65
Rosiglitazone		increase of AMP:ATP ratio	Complex I of the mitochondrial respiratory chain	63-65
Resveratrol		increase of AMP:ATP ratio	the mitochondrial F_1F_0-ATPase/ATP synthase	66,67,72,73
Quercetin		increase of AMP:ATP ratio	the mitochondrial F_1F_0-ATPase/ATP synthase	68,72,73
Genistein		increase of AMP:ATP ratio	the mitochondrial F_1F_0-ATPase/ATP synthase	69,72,73
Epigallocatechin gallate		increase of AMP:ATP ratio	the mitochondrial F_1F_0-ATPase/ATP synthase	69,72,73
Berberine		increase of AMP:ATP ratio	Complex I of the mitochondrial respiratory chain	70,74
Curcumin		increase of AMP:ATP ratio	the mitochondrial F_1F_0-ATPase/ATP synthase	71-73
Ginsenoside Rb1		increase of AMP:ATP ratio	unknown	75,76
α-lipoic acid		increase of cellular calcium level	unknown	77-82
Cryptotanshinone		increase of ROS	unknown	87,88

attributable to AMPK. Zhou *et al.* have revealed the molecular mechanisms by which AMPK mediates the antidiabetic actions of metformin: stimulation of fatty-acid oxidation and glucose uptake, and downregulation of lipogenic genes and hepatic glucose production.[58] AMPK activation by metformin is not a result of direct activation; instead, metformin inhibits complex I of the mitochondrial respiratory chain, leading to an increased AMP:ATP ratio.[59] This indirect mechanism has further been supported by the observation that metformin fails to activate AMPK in cells expressing the AMP-insensitive (R531G) AMPKγ2 subunit.[60] Recent findings by Fullerton *et al.* have also shown that phosphorylation of acetyl-CoA carboxylase by AMPK is required for the lipid-lowering effect and the insulin-sensitizing effects of metformin, thereby supporting the role of AMPK in metformin action. However, the role of AMPK has been called into question by recent work showing that metformin lowers blood glucose levels in animal models of liver-specific AMPKα knockout or LKB1 knockout.[61] Thus, further studies are required to distinguish the AMPK-dependent and -independent effects of metformin.

Table 2 Direct AMPK activators

Compound name	*Chemical structure*	*Target subunit*	*Isoform specificity*	*reference*
5-Aminoimidazole-4-carboxamide riboside (AICAR)		AMPKγ subunit (AMP-mimetic)	none	91,92
Thienopyridone (A-769662)		AMPKβ subunit	β1- subunit	98-102
Benzimidazole (Compound 911)		AMPKβ subunit	β1- subunit	12
Salicylate (Pro-drug of Asprin)		AMPKβ subunit	β1- subunit	103
Compound-13 (Pro-drug of C-2)		AMPKα subunit	α1- subunit	108,109
PT-1		AMPKβ subunit	γ1- subunit	111,112
MT 63-78 (Debio0930)		AMPKβ subunit	β1- subunit	113

Thiazolidinedione

Thiazolidinediones (TZDs), also known as glitazones, are a class of insulin-sensitizing drugs including troglitazone, pioglitazone and rosiglitazone. TZDs act primarily by activating the nuclear hormone receptor peroxisome proliferator-activated receptors (PPARs), notably PPARγ, for which their affinity is highest. They are also known to exert their antidiabetic effect in part through AMPK activation. TZDs rapidly activate AMPK in a variety of tissues including skeletal muscle,[62,63] liver and adipose tissue,[64] and the activation mechanisms are associated with accumulation of AMP as a result of inhibiting complex I of the mitochondrial respiratory chain.[65] In addition, TZD treatment induces the expression and release of adiponectin from adipocytes,[63] which in turn activates AMPK in skeletal muscle and the liver, resulting in increased glucose uptake and fatty-acid oxidation, and decreased hepatic glucose production. Thus, AMPK can be activated by TZDs through at least two different mechanisms.

Polyphenols

In addition to pharmaceutical agents, numerous naturally occurring compounds and phytochemicals have been shown to activate AMPK. Among them are polyphenols, a structural class of natural or synthetic products characterized by the presence of multiples of phenol structure units. Despite the structural variance, numerous polyphenols are capable of activating AMPK, and they exert beneficial effects on type 2 diabetes and metabolic syndrome. These include resveratrol from red grapes,[66,67] quercetin from many plant units including fruits, vegetables and grains,[68] genistein found in a number of plants such as soybeans,[69] epigallocatechin gallate from green tea,[69] berberine from *Coptis chinensis*[70] and curcumim from *Curcuma longa*.[71] Mechanisms of activation of AMPK by these compounds appear to require the elevation of AMP levels because many of these compounds are known to inhibit mitochondrial ATP production. Resveratrol, quercetin, epigallocatechin-3-gallate and curcumin target and inhibit the mitochondrial F_1F_0–ATPase/ATP synthase,[72,73] whereas berberine is associated with the inhibition of respiratory chain complex I.[74] The molecular mechanism of AMPK activation by resveratrol, berberine and quercetin has further been supported by the observation that these compounds fail to activate AMPK in cells expressing AMP-insensitive (R531G) AMPKγ2 subunit.[60]

Ginsenoside

Panax ginseng has been long known to have favorable effects in type 2 diabetes and metabolic syndrome. Ginsenosides, a class of tetracyclic triterpene glycosides, are the major pharmacological ingredients in ginseng. To date, more than 80 structurally different ginsenosides have been isolated from the plant genus *Panax*, and a number of ginsenosides, including Rb1, Rb2, Rc, Re, Rg1, Rg2 and Rg3, have been reported to activate AMPK, resulting in an increased glucose uptake, decreased hepatic triglyceride and cholesterol levels, and the inhibition of lipogenesis and hepatic glucose production.[75] The mechanisms for AMPK activation by ginsenosides are largely unknown; however, presumably these compounds are likely to activate AMPK via AMP-dependent mechanisms because the ginsenoside, Rb1, has been reported to increase the intracellular AMP:ATP ratio.[76]

α-Lipoic acid

α-Lipoic acid (ALA), a naturally occurring dithiol compound derived from octanoic acid, has a critical role in mitochondrial bioenergetics reactions by acting as a cofactor for pyruvate dehydrogenase and α-ketoglutarate dehydrogenase. Owing to its powerful antioxidant property, ALA has gained substantial attention for use in managing diabetic complications.[77] Recent studies have also demonstrated that ALA exerts beneficial effects on metabolic syndrome, lipotoxic cardiomyopathy and endothelial dysfunction through the activation of AMPK in various tissues.[78–80] Although the underlying mechanisms for AMPK regulation by ALA are poorly understood, Shen *et al.* have reported that ALA increases the intracellular calcium level in C2C12 myotubes, suggesting that CaMKK, but not LKB1, is responsible for AMPK activation.[81] In the hypothalamus, where AMPK is implicated in the regulation of appetite, ALA suppresses AMPK activity, leading to reduced food intake.[82] Further examination is required to understand the molecular mechanism of the regulation of AMPK by ALA.

Other AMPK modulators

Although intracellular energy levels are a major determinant of AMPK activity, AMPK is highly sensitive to the cellular level of reactive oxygen species (ROS).[83] In many cases, oxidative stress results in intracellular ATP depletion. However, recent studies have revealed that ROS can stimulate AMPK activity even without a decrease in cellular ATP.[84,85] Oxidative modification of the AMPKα subunit appears to be a major mechanism by which AMPK is activated under conditions of oxidative stress.[86] Therefore, any modulators capable of inducing intracellular ROS generation can activate AMPK without an associated decrease in ATP levels. Such a modulator is cryptotanshinone from *Salvia miltiorrhiza Bunge*, which exerts antidiabetic[87] and anticancer effects[88] through ROS-dependent AMPK activation. DNA-damaging agents, such as cisplatin[89] or metals, including arsenite, vanadate and cobalt,[90] activate AMPK through ROS generation.

DIRECT AMPK ACTIVATORS

Several AMPK activators directly bind to and activate AMPK without any significant change in cellular ATP, ADP or AMP levels. Instead, these activators induce conformation changes in the AMPK complex, leading to activation, possibly through a direct interaction with a specific subunit of AMPK (Table 2). The identification of A-769662 by Abbott Laboratories in 2006 provided a novel insight into the development of direct AMPK activators by demonstrating that AMPK activation with non-nucleotide ligands is possible. In addition, it opened up the possibility of developing an activator with AMPK heterotrimer specificity. Since then, numerous studies reporting direct AMPK activators have provided meaningful advances regarding isoform-specific modulators.

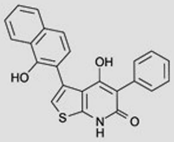
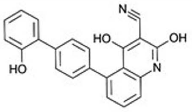
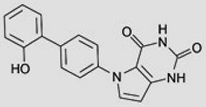
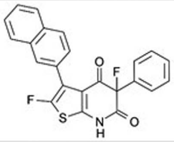
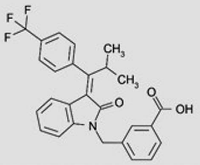
5-Aminoimidazole-4-carboxamide riboside

The first direct AMPK activator, 5-aminoimidazole-4-carboxamide riboside (AICAR), is an adenosine analog taken up into cells by adenosine transporters and phosphorylated by adenosine kinase, thus generating the AMP-mimetic, AICAR monophosphate (ZMP).[91,92] Similarly to cellular AMP, ZMP binds to site 3 on the AMPKγ subunit. ZMP does not change the ADP:ATP ratio or alter oxygen uptake, which occurs with many AMPK activators through the inhibition of mitochondrial function.[11] Although ZMP is a much less potent AMPK activator than AMP in cell-free systems, AICAR directly activates AMPK in most cells because ZMP can accumulate to millimolar concentrations in cells. ZMP is a natural intermediate in the purine nucleotide synthetic pathway and is metabolized by AICAR transformylase, which catalyzes synthesis of the purine nucleotide inosinate.[93] Therefore, the effect of AICAR seems to be more apparent in quiescent, primary cells than in rapidly proliferating cells. Consistently with this notion, anticancer agents that inhibit AICAR transformylase, such as methotrexate and Pemetrexed, sensitize tumor cells to the AMPK-activating and growth-inhibitory effects of AICAR.[94,95] These results indicate that AMPK participates in the chemotherapeutic effects of antifolate drugs to treat cancers. However, it should be noted that, as an AMP analog, AICAR is able to activate many other AMP-dependent enzymes, such as fructose-1,6-bisphosphatase.[96,97]

Thienopyridone (A-769662) and benzimidazole (Compound 911) derivatives

Abbott Laboratories has developed a thienopyridone compound, A-769662, which causes allosteric activation of purified AMPK in cell-free assays.[98] This compound shows many of the metabolic effects that would be expected with AMPK activation *in vivo* (increase in fat oxidation in normal rats; decreases in body weight, plasma glucose/triglycerides and liver triglycerides in obese mice). Unlike AICAR, A-769662 shows high specificity toward AMPK. A-769662, similar to AMP, allosterically activates the AMPK complex and inhibits dephosphorylation of Thr-172 in the AMPKα subunit.[99,100] However, A-769662 appears to use a different molecular mechanism to activate AMPK.[101] Notably, it allosterically activates AMPK without Thr172 phosphorylation on the AMPKα subunit, which is absolutely required for AMP-dependent AMPK activation. Importantly, it requires phosphorylation of Ser108 on the AMPKβ1 subunit. Moreover, the strong synergic AMPK

Table 3 Direct AMPK activators from patent literatures

Patent number	*A representative example*	In vitro *activity*	*First applicant*
WO 2009124636		Activation of recombinant AMPK α1β1γ2 at 30 μM: 625%	Merck Patent GMBH
WO 2009100130		Activation of partially purified AMPK: ED_{50} < 10 μM	Mercury Therapeutics Inc.
WO 2011029855 WO 2011138307		Activation of human recombinant AMPK (α1β1γ and α2β1γ2) pEC200 (-Log(compound : concentration leading to a 2-fold AMPK activity): 5.9	GlaxoSmithKline LLC.
WO 2011080277		AMPK Activity: Ratio between the % of control (basal activity) of compound of formula at 30μM and the % of control (basal activity) of AMP (natural substrate) at 200 μM	Poxel
WO 2011032320 WO 2011033099		Activation of human recombinant AMPK (α1β1γ and α2β1γ2) EC_{50}: 0.66 μM	Hoffmann-La Roche

activation by AMP and A-769662 has been observed both *in vitro* and *in vivo*, clearly demonstrating that A-769662 and AMP have different binding sites on the AMPK complex and different mechanisms of activation.[102] Another direct AMPK activator, compound 911, has recently been identified. 911 has been reported to be 5–10-fold more potent than A-769662 in allosterically activating AMPK and preventing dephosphorylation.[12] Similarly to A-769662, 991 does not activate AMPK complexes containing the Ser108 mutation of the AMPKβ subunit, suggesting that these two AMPK modulators share a similar molecular mechanism of AMPK activation. Xiao B *et al.*[12] have solved the crystal structure of the full-length human AMPK complex in the presence of A-769662 or 991. In this structure, both A-769662 and 911 are located at a site between the KD of the AMPKα subunit and the carbohydrate-binding module (CBM) of the β-subunit, a site distinct from the adenine nucleotide-binding sites on the AMPKγ subunit. Interestingly, both chemicals exhibit specificity toward AMPK complexes containing the β1 rather than the β2 isoform.

Salicylate (pro-drug of Asprin)

Salicylate is a natural compound traditionally extracted from willow bark. Acetyl salicylate (aspirin) is a derivative that is easier than salicylate to take orally and is rapidly broken down to salicylate upon entering the circulation. Although cyclo-oxygenases (COX1 and COX2) are the established targets for aspirin, it has been reported recently that salicylate (although not aspirin) is a direct activator of AMPK.[103] In line with its structural similarity to A-769662, salicylate appears to bind at a site that overlaps with the site targeted by A-769662. Both compounds cause allosteric activation, with salicylate antagonizing the effect of A-769662. In addition, the effects of both compounds are highly dependent on the AMPKβ1 subunit but not on AMPKβ2. Neither compound activates AMPK complexes with the Ser108 mutation of the AMPKβ1 subunit. Considering that thienopyridone (A-769662), benzimidazole (Compound 911) and salicylate derivatives activate AMPK by mechanisms different from most AMP-mimetics or ATP-depleting AMPK activators, the combination of these molecules with the indirect AMPK activators is expected to augment the effect of AMPK on pathophysiological conditions, such as metabolic disorders and cancers.[104–107]

Compound-13

Recent screening of a chemical library containing 1,200 AMP mimetics has identified 5-(5-hydroxyl-isoxazol-3-yl)-furan-2-phosphonic acid, termed Compound-2 (C-2), and its pro-drug C-13, as potent allosteric activators of AMPK.[108] A subsequent study has demonstrated the molecular mechanism by which C-2 mimics the effects of AMP to stimulate AMPK.[109] One concern, as observed with AICAR, is the possibility that C-2 may affect AMP-regulated enzymes other than AMPK (PFK1, FBP1 and glycogen phosphorylase). However, C-2 does not affect any of these enzymes or several enzymes that use AMP as a substrate. *In vitro* cell-free assays using several AMPK complexes have revealed that C-2 is a potent allosteric activator of AMPK (EC50 of 10–30 nM). In fact, C-2 has been reported to be >20-fold more potent than A769662 and more than two orders of magnitude more potent than AMP.[98,110] In addition, C-2 and C-13 do not induce any significant change in adenine nucleotide levels. Although the precise C-2-binding sites have not been identified, evidence presented by Hunter *et al.*[109] has suggested that C-2 competes with AMP for binding on the AMPKγ subunit. Surprisingly, the AMPK activators C-2 and C-13 exhibit isoform specificity toward the AMPKα1 subunit. Structural analyses of AMPK complexes[12,13] indicate that different sequences of AMPKα1 and α2 subunits in the α-regulatory subunit-interacting motif-2 (α-RIM2) region, which is used to generate AMPKα isoform-specific antibodies, result in unique interactions of C-2 with one face of AMP bound at Site 3 of the γ-subunit, accounting for the selectivity of C-2 toward AMPKα isoforms. Identification of C-2/C-13 represents an example of the development of a direct and isoform-specific AMPK modulator that is distinct from A-769662 that shows a CBM-dependent AMPKβ subunit specificity.[109]

PT-1

Another small molecule activator of AMPK, PT-1, was initially isolated via a screen of compounds that activated the truncated AMPKα1 construct containing only the KD and the AID.[111] PT-1 activates the complete AMPK α1β1γ1 as well as the AMPKα1 KD-AID construct but not the AMPKα1 KD construct, suggesting that PT-1 directly binds to the cleft between the KD and the AID, thereby relieving autoinhibition. Consistently with results from a cell-free kinase assay, PT-1 has been shown to increase the phosphorylation of ACC at Ser79, a well-characterized substrate of AMPK, in L6 myotubes without any significant change in cellular AMP:ATP ratio. However, this result has been questioned by a recent report by Jensen *et al.*[112] showing that PT-1 indirectly activates AMPK via inhibition of the mitochondrial respiratory chain complex, thereby increasing cellular AMP:ATP and/or ADP:ATP ratios, instead of binding directly to the AMPKα1 subunit, as previously suggested.[111] In line with the notion that PT-1 increases intracellular AMP levels, PT-1 does not activate AMPK in HEK293 cells expressing an AMP-insensitive AMPKγ1 R299G mutant, suggesting that PT-1 functions as an indirect activator. Furthermore, this study has shown that PT-1 selectively activates the AMPK complex containing the γ1-subunit but not γ3 in incubated mouse muscle. The authors have proposed that the failure of PT-1 to activate γ3-containing complexes in muscle is not an intrinsic feature of such complexes but occurs because PT-1 does not increase cellular AMP:ATP ratios in the distinct subcellular compartments containing γ3-complexes. Therefore, the molecular details of PT-1 action should be further studied to address the questions raised by these contradictory results.

MT 63–78 (Debio0930)

Another AMPK direct modulator, MT 63–78 (Debio0930), has recently been identified to allosterically activate AMPK.[113] Biochemical analysis has shown that the effect of MT 68–78 is highly selective for the AMPK complex containing the AMPKβ1 subunit, as was seen for A-769662 and salicylate. Notably, MT 63–78 strongly suppresses the growth of prostate cancer cell lines with a concomitant activation of AMPK but without any significant change in cellular ATP, ADP and AMP levels. Importantly, the growth-inhibitory effects of MT 63–78 on prostate cancers are at least 10–40 times higher than those of A-769662. In many prostate cancer models, androgen is believed to drive tumorigenesis and progression of the cancers.[114] Therefore, androgen deprivation therapy is a first option to treat this cancer. However, in many cases, the androgen-signaling cascade is re-activated after chemotherapeutic treatments that target the androgen receptor, for example, the androgen receptor antagonist MDV3100.[115] Upregulation of *de novo* lipogenesis by androgen in prostate cancer is also closely related to cancer development.[116,117] Considering that AMPK negatively regulates *de novo* lipogenesis,[92,108,118,119] the combination treatment of AMPK activators and androgen receptor inhibitors may function cooperatively as antiprostate cancer drugs. The clinical potential of this concept has been shown in a therapeutic trial. This trial showed that the suppression of *de novo* lipogenesis is the key mechanism of AMPK inhibition of growth and that MT 63–78 enhances the inhibitory effect of androgen receptor antagonist (MDV3100) on the growth of prostate cancer cells. In addition, the inhibitory effect of MT 63–78 on growth is not limited to prostate cancer cells and has also been observed in LKB1-null A549 cells and in B-RAF-mutated (V600E) KTC-1 cells. These results suggest that MT 63–78 slows the growth of a wide spectrum of cancers, thus increasing the chemotherapeutic effects of current anticancer drugs.

PERSPECTIVE

Most of the current agents that have been shown to activate AMPK in physiological trials, such as metformin, TZDs and 2-deoxyglucose, are indirect activators that inhibit oxidative phosphorylation and glycolysis, thereby increasing the ADP (AMP):ATP ratio. However, it is not always clear whether the effects of these agents are mediated by AMPK. In this sense, much effort has been focused on demonstrating the molecular mechanisms of AMPK activators and on validating the resulting physiologies on many human diseases.[2,120] Another concern when developing AMPK activators is that there are functional differences between isoform-specific AMPK complexes. For instance, the AMPK α2β2γ3 complex is predominantly activated by exercise in skeletal muscle,[5] and therefore specific targeting of the AMPK α2β2γ3. Recent studies reporting direct AMPK activators have provided meaningful advances in developing isoform-specific modulators. For the AMPKα subunit, C-2 (or a pro-drug C-13) has a preference for AMPK complexes containing the AMPKα1 subunit.[108] Similarly to A-769662,[98] several compounds including 911,[12] salicylate (a pro-drug of aspirin)[103] and MT 68–78[113] specifically activate AMPKβ1-containing complexes but not those containing AMPKβ2. In the case of the AMPKγ subunit, although further studies at the cellular level are required, *in vitro* biochemical data have shown that PT-1 has a specificity toward AMPK complexes harboring the AMPKγ1 subunit.[111] In addition to these activators, a number of pharmaceutical companies have filed patent applications for novel AMPK activators, which are structurally unrelated to AMP. Some representative compounds from each pharmaceutical company are listed in Table 3. Comprehensive lists of AMPK activators in the patent literature are available elsewhere.[121,122] It is highly intriguing that, although they have been claimed to be novel, the majority of the direct AMPK activators listed in Table 3 show a close resemblance to the original thienopyridone core structure of A-769662, except for the alkene oxindole derivative reported from F. Hoffmann-La Roche AG. Given the recent reports suggesting the AMPK-independent effects of A-769662,[100,123] further studies are needed to clarify the molecular basis of the accumulating number of direct AMPK activators, by comparing their activation mechanisms and by analyzing their profiles of selectivity across AMPK complex combinations.

One interesting aspect of AMPK activators revealed by preclinical studies is the enhanced therapeutic effects of the combination of different AMPK activators. As a master regulator of lipogenic pathway,[25] AMPK may be an additional chemotherapeutic target because the upregulation of fatty-acid synthesis is a hallmark of many cancers.[124] Evidence has shown that the combination of aspirin (salicylate) and Metformin effectively decreases clonogenic survival of prostate and lung cancer cells.[104] Consistently with this finding, the addition of fatty acids and/or cholesterol into the culture medium reverses the suppressive effects of salicylate and metformin on cell survival, indicating that the inhibition of *de novo* lipogenesis is important.[105,106] Similarly, direct AMPK activators may open new therapeutic avenues for antichemotherapeutic reagents. In the case of the conventional indirect AMPK activators, the mechanism of action requires the upstream kinase LKB1 for physiological AMPK activation. Therefore, the potential of indirect AMPK activators as anticancer drugs is limited to LKB1-deficient tumors, especially for non-small cell lung cancers, of which more than 30% have LKB1-inactivating mutations. In this aspect, direct AMPK activators may overcome this limitation. The evidence shows that the growth-inhibitory response to the AMPK activator, MT 63–78, is not affected by the status of the upstream AMPK-activating kinase LKB1.

In conclusion, the recent advances identifying direct AMPK activators make AMPK a 'druggable' target for many human diseases, although further studies are required to gain insight into the molecular mechanisms by which AMPK regulates its distinct and diverse downstream targets to produce physiological outcomes.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ACKNOWLEDGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant, funded by the Korea government (MEST, No 2012R1A5A2051387 to JK, and MEST, No 2011-0030072 to JH).

---

1 Hardie DG, Ross FA, Hawley SA. AMPK: a nutrient and energy sensor that maintains energy homeostasis. *Nat Rev Mol Cell Biol* 2012; **13**: 251–262.
2 Mihaylova MM, Shaw RJ. The AMPK signalling pathway coordinates cell growth, autophagy and metabolism. *Nat Cell Biol* 2011; **13**: 1016–1023.
3 Vazquez-Martin A, Oliveras-Ferraros C, Menendez JA. The active form of the metabolic sensor: AMP-activated protein kinase (AMPK) directly binds the mitotic apparatus and travels from centrosomes to the spindle midzone during mitosis and cytokinesis. *Cell Cycle* 2009; **8**: 2385–2398.
4 Salt I, Celler JW, Hawley SA, Prescott A, Woods A, Carling D *et al.* AMP-activated protein kinase: greater AMP dependence, and preferential nuclear localization, of complexes containing the alpha2 isoform. *Biochem J* 1998; **334**(Pt 1): 177–187.
5 Birk JB, Wojtaszewski JF. Predominant alpha2/beta2/gamma3 AMPK activation during exercise in human skeletal muscle. *J Physiol* 2006; **577**(Pt 3): 1021–1032.
6 Burwinkel B, Scott JW, Buhrer C, van Landeghem FK, Cox GF, Wilson CJ *et al.* Fatal congenital heart glycogenosis caused by a recurrent activating R531Q mutation in the gamma 2-subunit of AMP-activated protein kinase (PRKAG2), not by phosphorylase kinase deficiency. *Am J Hum Genet* 2005; **76**: 1034–1049.
7 Steinberg GR, O'Neill HM, Dzamko NL, Galic S, Naim T, Koopman R *et al.* Whole body deletion of AMP-activated protein kinase {beta}2 reduces muscle AMPK activity and exercise capacity. *J Biol Chem* 2010; **285**: 37198–37209.
8 Barnes BR, Marklund S, Steiler TL, Walter M, Hjalm G, Amarger V *et al.* The 5′-AMP-activated protein kinase gamma3 isoform has a key role in carbohydrate and lipid metabolism in glycolytic skeletal muscle. *J Biol Chem* 2004; **279**: 38441–38447.
9 Hawley SA, Davison M, Woods A, Davies SP, Beri RK, Carling D *et al.* Characterization of the AMP-activated protein kinase kinase from rat liver and identification of threonine 172 as the major site at which it phosphorylates AMP-activated protein kinase. *J Biol Chem* 1996; **271**: 27879–27887.
10 Stein SC, Woods A, Jones NA, Davison MD, Carling D. The regulation of AMP-activated protein kinase by phosphorylation. *Biochem J* 2000; **345** (Pt 3): 437–443.
11 Xiao B, Heath R, Saiu P, Leiper FC, Leone P, Jing C *et al.* Structural basis for AMP binding to mammalian AMP-activated protein kinase. *Nature* 2007; **449**: 496–500.
12 Xiao B, Sanders MJ, Carmena D, Bright NJ, Haire LF, Underwood E *et al.* Structural basis of AMPK regulation by small molecule activators. *Nat Commun* 2013; **4**: 3017.
13 Xiao B, Sanders MJ, Underwood E, Heath R, Mayer FV, Carmena D *et al.* Structure of mammalian AMPK and its regulation by ADP. *Nature* 2011; **472**: 230–233.
14 Ignoul S, Eggermont J. CBS domains: structure, function, and pathology in human proteins. *Am J Physiol Cell Physiol* 2005; **289**: C1369–C1378.
15 Viana R, Towler MC, Pan DA, Carling D, Viollet B, Hardie DG *et al.* A conserved sequence immediately N-terminal to the Bateman domains in AMP-activated protein kinase gamma subunits is required for the interaction with the beta subunits. *J Biol Chem* 2007; **282**: 16117–16125.
16 Oakhill JS, Scott JW, Kemp BE. AMPK functions as an adenylate charge-regulated protein kinase. *Trends Endocrinol Metab* 2012; **23**: 125–132.
17 Gowans GJ, Hawley SA, Ross FA, Hardie DG. AMP is a true physiological regulator of AMP-activated protein kinase by both allosteric activation and enhancing net phosphorylation. *Cell Metab* 2013; **18**: 556–566.
18 Hawley SA, Boudeau J, Reid JL, Mustard KJ, Udd L, Makela TP *et al.* Complexes between the LKB1 tumor suppressor, STRAD alpha/beta and MO25 alpha/beta are upstream kinases in the AMP-activated protein kinase cascade. *J Biol* 2003; **2**: 28.
19 Woods A, Dickerson K, Heath R, Hong SP, Momcilovic M, Johnstone SR *et al.* Ca^{2+}/calmodulin-dependent protein kinase kinase-beta acts

upstream of AMP-activated protein kinase in mammalian cells. *Cell Metab* 2005; **2**: 21–33.
20 Hawley SA, Selbert MA, Goldstein EG, Edelman AM, Carling D, Hardie DG. 5′-AMP activates the AMP-activated protein kinase cascade, and Ca^{2+}/calmodulin activates the calmodulin-dependent protein kinase I cascade, via three independent mechanisms. *J Biol Chem* 1995; **270**: 27186–27191.
21 Davies SP, Helps NR, Cohen PT, Hardie DG. 5′-AMP inhibits dephosphorylation, as well as promoting phosphorylation, of the AMP-activated protein kinase. Studies using bacterially expressed human protein phosphatase-2C alpha and native bovine protein phosphatase-2AC. *FEBS Lett* 1995; **377**: 421–425.
22 Oakhill JS, Steel R, Chen ZP, Scott JW, Ling N, Tam S *et al.* AMPK is a direct adenylate charge-regulated protein kinase. *Science* 2011; **332**: 1433–1435.
23 Towler MC, Hardie DG. AMP-activated protein kinase in metabolic control and insulin signaling. *Circ Res* 2007; **100**: 328–341.
24 Fogarty S, Hardie DG. Development of protein kinase activators: AMPK as a target in metabolic disorders and cancer. *Biochim Biophys Acta* 2010; **1804**: 581–591.
25 Hardie DG. AMPK: a key regulator of energy balance in the single cell and the whole organism. *Int J Obes (Lond)* 2008; **32**(Suppl 4): S7–12.
26 Hardie DG. Energy sensing by the AMP-activated protein kinase and its effects on muscle metabolism. *Proc Nutr Soc* 2011; **70**: 92–99.
27 Hardie DG. AMP-activated protein kinase: maintaining energy homeostasis at the cellular and whole-body levels. *Annu Rev Nutr* 2014; **34**: 31–55.
28 Hardie DG. AMP-activated protein kinase: a master switch in glucose and lipid metabolism. *Rev Endocr Metab Disord* 2004; **5**: 119–125.
29 Musi N, Goodyear LJ. Targeting the AMP-activated protein kinase for the treatment of type 2 diabetes. *Curr Drug Targets Immune Endocr Metabol Disord* 2002; **2**: 119–127.
30 Musi N. AMP-activated protein kinase and type 2 diabetes. *Curr Med Chem* 2006; **13**: 583–589.
31 Rehman G, Shehzad A, Khan AL, Hamayun M. Role of AMP-activated protein kinase in cancer therapy. *Arch Pharm (Weinheim)* 2014; **347**: 457–468.
32 Alessi DR, Sakamoto K, Bayascas JR. LKB1-dependent signaling pathways. *Annu Rev Biochem* 2006; **75**: 137–163.
33 Hemminki A. The molecular basis and clinical aspects of Peutz-Jeghers syndrome. *Cell Mol Life Sci* 1999; **55**: 735–750.
34 Evans JM, Donnelly LA, Emslie-Smith AM, Alessi DR, Morris AD. Metformin and reduced risk of cancer in diabetic patients. *Br Med J* 2005; **330**: 1304–1305.
35 Huang X, Wullschleger S, Shpiro N, McGuire VA, Sakamoto K, Woods YL *et al.* Important role of the LKB1-AMPK pathway in suppressing tumorigenesis in PTEN-deficient mice. *Biochem J* 2008; **412**: 211–221.
36 Gwinn DM, Shackelford DB, Egan DF, Mihaylova MM, Mery A, Vasquez DS *et al.* AMPK phosphorylation of raptor mediates a metabolic checkpoint. *Mol Cell* 2008; **30**: 214–226.
37 Inoki K, Zhu T, Guan KL. TSC2 mediates cellular energy response to control cell growth and survival. *Cell* 2003; **115**: 577–590.
38 Hoppe S, Bierhoff H, Cado I, Weber A, Tiebe M, Grummt I *et al.* AMP-activated protein kinase adapts rRNA synthesis to cellular energy supply. *Proc Natl Acad Sci USA* 2009; **106**: 17781–17786.
39 Jones RG, Plas DR, Kubek S, Buzzai M, Mu J, Xu Y *et al.* AMP-activated protein kinase induces a p53-dependent metabolic checkpoint. *Mol Cell* 2005; **18**: 283–293.
40 Imamura K, Ogura T, Kishimoto A, Kaminishi M, Esumi H. Cell cycle regulation via p53 phosphorylation by a 5′-AMP activated protein kinase activator, 5-aminoimidazole- 4-carboxamide-1-beta-D-ribofuranoside, in a human hepatocellular carcinoma cell line. *Biochem Biophys Res Commun* 2001; **287**: 562–567.
41 Liang J, Shao SH, Xu ZX, Hennessy B, Ding Z, Larrea M *et al.* The energy sensing LKB1-AMPK pathway regulates p27(kip1) phosphorylation mediating the decision to enter autophagy or apoptosis. *Nat Cell Biol* 2007; **9**: 218–224.
42 Budanov AV, Karin M. p53 target genes sestrin1 and sestrin2 connect genotoxic stress and mTOR signaling. *Cell* 2008; **134**: 451–460.
43 He C, Klionsky DJ. Regulation mechanisms and signaling pathways of autophagy. *Annu Rev Genet* 2009; **43**: 67–93.
44 Kroemer G, Marino G, Levine B. Autophagy and the integrated stress response. *Mol Cell* 2010; **40**: 280–293.
45 Mizushima N, Levine B. Autophagy in mammalian development and differentiation. *Nat Cell Biol* 2010; **12**: 823–830.
46 Galluzzi L, Pietrocola F, Levine B, Kroemer G. Metabolic control of autophagy. *Cell* 2014; **159**: 1263–1276.
47 Kim J, Kundu M, Viollet B, Guan KL. AMPK and mTOR regulate autophagy through direct phosphorylation of Ulk1. *Nat Cell Biol* 2011; **13**: 132–141.
48 Egan DF, Shackelford DB, Mihaylova MM, Gelino S, Kohnz RA, Mair W *et al.* Phosphorylation of ULK1 (hATG1) by AMP-activated protein kinase connects energy sensing to mitophagy. *Science* 2011; **331**: 456–461.
49 Kim J, Kim YC, Fang C, Russell RC, Kim JH, Fan W *et al.* Differential regulation of distinct Vps34 complexes by AMPK in nutrient stress and autophagy. *Cell* 2013; **152**: 290–303.
50 Ha J, Guan KL, Kim J. AMPK and autophagy in glucose/glycogen metabolism. *Mol Aspects Med* 2015; **46**: 46–62.
51 Singh R, Kaushik S, Wang Y, Xiang Y, Novak I, Komatsu M *et al.* Autophagy regulates lipid metabolism. *Nature* 2009; **458**: 1131–1135.
52 Singh R, Xiang Y, Wang Y, Baikati K, Cuervo AM, Luu YK *et al.* Autophagy regulates adipose mass and differentiation in mice. *J Clin Invest* 2009; **119**: 3329–3339.
53 Kim J, Shin J, Ha J. Screening methods for AMP-activated protein kinase modulators: a patent review. *Expert Opin Ther Pat* 2015; **25**: 261–277.
54 Sinnett SE, Brenman JE. Past strategies and future directions for identifying AMP-activated protein kinase (AMPK) modulators. *Pharmacol Ther* 2014; **143**: 111–118.
55 Hardie DG. AMP-activated protein kinase as a drug target. *Annu Rev Pharmacol Toxicol* 2007; **47**: 185–210.
56 Sriwijitkamol A, Musi N. Advances in the development of AMPK-activating compounds. *Expert Opin Drug Discov* 2008; **3**: 1167–1176.
57 Foretz M, Guigas B, Bertrand L, Pollak M, Viollet B. Metformin: from mechanisms of action to therapies. *Cell Metab* 2014; **20**: 953–966.
58 Zhou G, Myers R, Li Y, Chen Y, Shen X, Fenyk-Melody J *et al.* Role of AMP-activated protein kinase in mechanism of metformin action. *J Clin Invest* 2001; **108**: 1167–1174.
59 Owen MR, Doran E, Halestrap AP. Evidence that metformin exerts its anti-diabetic effects through inhibition of complex 1 of the mitochondrial respiratory chain. *Biochem J* 2000; **348**(Pt 3): 607–614.
60 Hawley SA, Ross FA, Chevtzoff C, Green KA, Evans A, Fogarty S *et al.* Use of cells expressing gamma subunit variants to identify diverse mechanisms of AMPK activation. *Cell Metab* 2010; **11**: 554–565.
61 Foretz M, Hebrard S, Leclerc J, Zarrinpashneh E, Soty M, Mithieux G *et al.* Metformin inhibits hepatic gluconeogenesis in mice independently of the LKB1/AMPK pathway via a decrease in hepatic energy state. *J Clin Invest* 2010; **120**: 2355–2369.
62 Fryer LG, Parbu-Patel A, Carling D. The Anti-diabetic drugs rosiglitazone and metformin stimulate AMP-activated protein kinase through distinct signaling pathways. *J Biol Chem* 2002; **277**: 25226–25232.
63 LeBrasseur NK, Kelly M, Tsao TS, Farmer SR, Saha AK, Ruderman NB *et al.* Thiazolidinediones can rapidly activate AMP-activated protein kinase in mammalian tissues. *Am J Physiol Endocrinol Metab* 2006; **291**: E175–E181.
64 Saha AK, Avilucea PR, Ye JM, Assifi MM, Kraegen EW, Ruderman NB. Pioglitazone treatment activates AMP-activated protein kinase in rat liver and adipose tissue *in vivo*. *Biochem Biophys Res Commun* 2004; **314**: 580–585.
65 Brunmair B, Staniek K, Gras F, Scharf N, Althaym A, Clara R *et al.* Thiazolidinediones, like metformin, inhibit respiratory complex I: a common mechanism contributing to their antidiabetic actions? *Diabetes* 2004; **53**: 1052–1059.
66 Baur JA, Pearson KJ, Price NL, Jamieson HA, Lerin C, Kalra A *et al.* Resveratrol improves health and survival of mice on a high-calorie diet. *Nature* 2006; **444**: 337–342.
67 Park CE, Kim MJ, Lee JH, Min BI, Bae H, Choe W *et al.* Resveratrol stimulates glucose transport in C2C12 myotubes by activating AMP-activated protein kinase. *Exp Mol Med* 2007; **39**: 222–229.
68 Ahn J, Lee H, Kim S, Park J, Ha T. The anti-obesity effect of quercetin is mediated by the AMPK and MAPK signaling pathways. *Biochem Biophys Res Commun* 2008; **373**: 545–549.

69 Hwang JT, Park IJ, Shin JI, Lee YK, Lee SK, Baik HW *et al.* Genistein, EGCG, and capsaicin inhibit adipocyte differentiation process via activating AMP-activated protein kinase. *Biochem Biophys Res Commun* 2005; **338**: 694–699.
70 Lee YS, Kim WS, Kim KH, Yoon MJ, Cho HJ, Shen Y *et al.* Berberine, a natural plant product, activates AMP-activated protein kinase with beneficial metabolic effects in diabetic and insulin-resistant states. *Diabetes* 2006; **55**: 2256–2264.
71 Kim T, Davis J, Zhang AJ, He X, Mathews ST. Curcumin activates AMPK and suppresses gluconeogenic gene expression in hepatoma cells. *Biochem Biophys Res Commun* 2009; **388**: 377–382.
72 Gledhill JR, Montgomery MG, Leslie AG, Walker JE. Mechanism of inhibition of bovine F1-ATPase by resveratrol and related polyphenols. *Proc Natl Acad Sci USA* 2007; **104**: 13632–13637.
73 Zheng J, Ramirez VD. Inhibition of mitochondrial proton F0F1-ATPase/ATP synthase by polyphenolic phytochemicals. *Br J Pharmacol* 2000; **130**: 1115–1123.
74 Turner N, Li JY, Gosby A, To SW, Cheng Z, Miyoshi H *et al.* Berberine and its more biologically available derivative, dihydroberberine, inhibit mitochondrial respiratory complex I: a mechanism for the action of berberine to activate AMP-activated protein kinase and improve insulin action. *Diabetes* 2008; **57**: 1414–1418.
75 Jeong KJ, Kim GW, Chung SH. AMP-activated protein kinase: an emerging target for ginseng. *J Ginseng Res* 2014; **38**: 83–88.
76 Shen L, Xiong Y, Wang DQ, Howles P, Basford JE, Wang J *et al.* Ginsenoside Rb1 reduces fatty liver by activating AMP-activated protein kinase in obese rats. *J Lipid Res* 2013; **54**: 1430–1438.
77 Golbidi S, Badran M, Laher I. Diabetes and alpha lipoic acid. *Front Pharmacol* 2011; **2**: 69.
78 Lee WJ, Song KH, Koh EH, Won JC, Kim HS, Park HS *et al.* Alpha-lipoic acid increases insulin sensitivity by activating AMPK in skeletal muscle. *Biochem Biophys Res Commun* 2005; **332**: 885–891.
79 Lee Y, Naseem RH, Park BH, Garry DJ, Richardson JA, Schaffer JE *et al.* Alpha-lipoic acid prevents lipotoxic cardiomyopathy in acyl CoA-synthase transgenic mice. *Biochem Biophys Res Commun* 2006; **344**: 446–452.
80 Lee WJ, Lee IK, Kim HS, Kim YM, Koh EH, Won JC *et al.* Alpha-lipoic acid prevents endothelial dysfunction in obese rats via activation of AMP-activated protein kinase. *Arterioscler Thromb Vasc Biol* 2005; **25**: 2488–2494.
81 Shen QW, Zhu MJ, Tong J, Ren J, Du M. Ca^{2+}/calmodulin-dependent protein kinase kinase is involved in AMP-activated protein kinase activation by alpha-lipoic acid in C2C12 myotubes. *Am J Physiol Cell Physiol* 2007; **293**: C1395–C1403.
82 Kim MS, Park JY, Namkoong C, Jang PG, Ryu JW, Song HS *et al.* Anti-obesity effects of alpha-lipoic acid mediated by suppression of hypothalamic AMP-activated protein kinase. *Nat Med* 2004; **10**: 727–733.
83 Choi SL, Kim SJ, Lee KT, Kim J, Mu J, Birnbaum MJ *et al.* The regulation of AMP-activated protein kinase by H(2)O(2). *Biochem Biophys Res Commun* 2001; **287**: 92–97.
84 Wu Y, Viana M, Thirumangalathu S, Loeken MR. AMP-activated protein kinase mediates effects of oxidative stress on embryo gene expression in a mouse model of diabetic embryopathy. *Diabetologia* 2012; **55**: 245–254.
85 Quintero M, Colombo SL, Godfrey A, Moncada S. Mitochondria as signaling organelles in the vascular endothelium. *Proc Natl Acad Sci USA* 2006; **103**: 5379–5384.
86 Zmijewski JW, Banerjee S, Bae H, Friggeri A, Lazarowski ER, Abraham E. Exposure to hydrogen peroxide induces oxidation and activation of AMP-activated protein kinase. *J Biol Chem* 2010; **285**: 33154–33164.
87 Kim EJ, Jung SN, Son KH, Kim SR, Ha TY, Park MG *et al.* Antidiabetes and antiobesity effect of cryptotanshinone via activation of AMP-activated protein kinase. *Mol Pharmacol* 2007; **72**: 62–72.
88 Park IJ, Yang WK, Nam SH, Hong J, Yang KR, Kim J *et al.* Cryptotanshinone induces G1 cell cycle arrest and autophagic cell death by activating the AMP-activated protein kinase signal pathway in HepG2 hepatoma. *Apoptosis* 2014; **19**: 615–628.
89 Kim HS, Hwang JT, Yun H, Chi SG, Lee SJ, Kang I *et al.* Inhibition of AMP-activated protein kinase sensitizes cancer cells to cisplatin-induced apoptosis via hyper-induction of p53. *J Biol Chem* 2008; **283**: 3731–3742.
90 Lee M, Hwang JT, Yun H, Kim EJ, Kim MJ, Kim SS *et al.* Critical roles of AMP-activated protein kinase in the carcinogenic metal-induced expression of VEGF and HIF-1 proteins in DU145 prostate carcinoma. *Biochem Pharmacol* 2006; **72**: 91–103.
91 Corton JM, Gillespie JG, Hawley SA, Hardie DG. 5-aminoimidazole-4-carboxamide ribonucleoside. A specific method for activating AMP-activated protein kinase in intact cells? *Eur J Biochem* 1995; **229**: 558–565.
92 Sullivan JE, Brocklehurst KJ, Marley AE, Carey F, Carling D, Beri RK. Inhibition of lipolysis and lipogenesis in isolated rat adipocytes with AICAR, a cell-permeable activator of AMP-activated protein kinase. *FEBS Lett* 1994; **353**: 33–36.
93 Marie S, Heron B, Bitoun P, Timmerman T, Van Den Berghe G, Vincent MF. AICA-ribosiduria: a novel, neurologically devastating inborn error of purine biosynthesis caused by mutation of ATIC. *Am J Hum Genet* 2004; **74**: 1276–1281.
94 Beckers A, Organe S, Timmermans L, Vanderhoydonc F, Deboel L, Derua R *et al.* Methotrexate enhances the antianabolic and antiproliferative effects of 5-aminoimidazole-4-carboxamide riboside. *Mol Cancer Ther* 2006; **5**: 2211–2217.
95 McGuire JJ, Haile WH, Yeh CC. 5-amino-4-imidazolecarboxamide riboside potentiates both transport of reduced folates and antifolates by the human reduced folate carrier and their subsequent metabolism. *Cancer Res* 2006; **66**: 3836–3844.
96 Vincent MF, Marangos PJ, Gruber HE, Van den Berghe G. Inhibition by AICA riboside of gluconeogenesis in isolated rat hepatocytes. *Diabetes* 1991; **40**: 1259–1266.
97 Vincent MF, Bontemps F, Van den Berghe G. Inhibition of glycolysis by 5-amino-4-imidazolecarboxamide riboside in isolated rat hepatocytes. *Biochem J* 1992; **281**(Pt 1): 267–272.
98 Cool B, Zinker B, Chiou W, Kifle L, Cao N, Perham M *et al.* Identification and characterization of a small molecule AMPK activator that treats key components of type 2 diabetes and the metabolic syndrome. *Cell Metab* 2006; **3**: 403–416.
99 Scott JW, van Denderen BJ, Jorgensen SB, Honeyman JE, Steinberg GR, Oakhill JS *et al.* Thienopyridone drugs are selective activators of AMP-activated protein kinase beta1-containing complexes. *Chem Biol* 2008; **15**: 1220–1230.
100 Moreno D, Knecht E, Viollet B, Sanz P. A769662, a novel activator of AMP-activated protein kinase, inhibits non-proteolytic components of the 26S proteasome by an AMPK-independent mechanism. *FEBS Lett* 2008; **582**: 2650–2654.
101 Scott JW, Ling N, Issa SM, Dite TA, O'Brien MT, Chen ZP *et al.* Small molecule drug A-769662 and AMP synergistically activate naive AMPK independent of upstream kinase signaling. *Chem Biol* 2014; **21**: 619–627.
102 Sanders MJ, Ali ZS, Hegarty BD, Heath R, Snowden MA, Carling D. Defining the mechanism of activation of AMP-activated protein kinase by the small molecule A-769662, a member of the thienopyridone family. *J Biol Chem* 2007; **282**: 32539–32548.
103 Hawley SA, Fullerton MD, Ross FA, Schertzer JD, Chevtzoff C, Walker KJ *et al.* The ancient drug salicylate directly activates AMP-activated protein kinase. *Science* 2012; **336**: 918–922.
104 O'Brien AJ, Villani LA, Broadfield LA, Houde VP, Galic S, Blandino G *et al.* Salicylate activates AMPK and synergizes with metformin to reduce the survival of prostate and lung cancer cells *ex vivo* through inhibition of *de novo* lipogenesis. *Biochem J* 2015; **469**: 177–187.
105 Fullerton MD, Ford RJ, McGregor CP, LeBlond ND, Snider SA, Stypa SA *et al.* Salicylate improves macrophage cholesterol homeostasis via activation of Ampk. *J Lipid Res* 2015; **56**: 1025–1033.
106 Ford RJ, Fullerton MD, Pinkosky SL, Day EA, Scott JW, Oakhill JS *et al.* Metformin and salicylate synergistically activate liver AMPK, inhibit lipogenesis and improve insulin sensitivity. *Biochem J* 2015; **468**: 125–132.
107 Serizawa Y, Oshima R, Yoshida M, Sakon I, Kitani K, Goto A *et al.* Salicylate acutely stimulates 5′-AMP-activated protein kinase and insulin-independent glucose transport in rat skeletal muscles. *Biochem Biophys Res Commun* 2014; **453**: 81–85.
108 Gomez-Galeno JE, Dang Q, Nguyen TH, Boyer SH, Grote MP, Sun Z *et al.* A potent and selective AMPK activator that inhibits *de novo* lipogenesis. *ACS Med Chem Lett* 2010; **1**: 478–482.
109 Hunter RW, Foretz M, Bultot L, Fullerton MD, Deak M, Ross FA *et al.* Mechanism of action of compound-13: an alpha1-selective small molecule activator of AMPK. *Chem Biol* 2014; **21**: 866–879.
110 Goransson O, McBride A, Hawley SA, Ross FA, Shpiro N, Foretz M *et al.* Mechanism of action of A-769662, a valuable tool for activation of AMP-activated protein kinase. *J Biol Chem* 2007; **282**: 32549–32560.

111 Pang T, Zhang ZS, Gu M, Qiu BY, Yu LF, Cao PR *et al.* Small molecule antagonizes autoinhibition and activates AMP-activated protein kinase in cells. *J Biol Chem* 2008; **283**: 16051–16060.
112 Jensen TE, Ross FA, Kleinert M, Sylow L, Knudsen JR, Gowans GJ *et al.* PT-1 selectively activates AMPK-gamma1 complexes in mouse skeletal muscle, but activates all three gamma subunit complexes in cultured human cells by inhibiting the respiratory chain. *Biochem J* 2015; **467**: 461–472.
113 Zadra G, Photopoulos C, Tyekucheva S, Heidari P, Weng QP, Fedele G *et al.* A novel direct activator of AMPK inhibits prostate cancer growth by blocking lipogenesis. *EMBO Mol Med* 2014; **6**: 519–538.
114 Yuan X, Cai C, Chen S, Yu Z, Balk SP. Androgen receptor functions in castration-resistant prostate cancer and mechanisms of resistance to new agents targeting the androgen axis. *Oncogene* 2014; **33**: 2815–2825.
115 Higano CS, Crawford ED. New and emerging agents for the treatment of castration-resistant prostate cancer. *Urol Oncol* 2011; **29**(6 Suppl): S1–S8.
116 Swinnen JV, Ulrix W, Heyns W, Verhoeven G. Coordinate regulation of lipogenic gene expression by androgens: evidence for a cascade mechanism involving sterol regulatory element binding proteins. *Proc Natl Acad Sci USA* 1997; **94**: 12975–12980.
117 Ettinger SL, Sobel R, Whitmore TG, Akbari M, Bradley DR, Gleave ME *et al.* Dysregulation of sterol response element-binding proteins and downstream effectors in prostate cancer during progression to androgen independence. *Cancer Res* 2004; **64**: 2212–2221.
118 Menendez JA, Lupu R. Fatty acid synthase and the lipogenic phenotype in cancer pathogenesis. *Nat Rev Cancer* 2007; **7**: 763–777.
119 Zadra G, Priolo C, Patnaik A, Loda M. New strategies in prostate cancer: targeting lipogenic pathways and the energy sensor AMPK. *Clin Cancer Res* 2010; **16**: 3322–3328.
120 Hardie DG. AMPK: positive and negative regulation, and its role in whole-body energy homeostasis. *Curr Opin Cell Biol* 2015; **33**: 1–7.
121 Yun H, Ha J. AMP-activated protein kinase modulators: a patent review (2006–2010). *Expert Opin Ther Pat* 2011; **21**: 983–1005.
122 Giordanetto F, Karis D. Direct AMP-activated protein kinase activators: a review of evidence from the patent literature. *Expert Opin Ther Pat* 2012; **22**: 1467–1477.
123 Benziane B, Bjornholm M, Lantier L, Viollet B, Zierath JR, Chibalin AV. AMP-activated protein kinase activator A-769662 is an inhibitor of the Na(+)-K(+)-ATPase. *Am J Physiol Cell Physiol* 2009; **297**: C1554–C1566.
124 Santos CR, Schulze A. Lipid metabolism in cancer. *FEBS J* 2012; **279**: 2610–2623.