MINIREVIEW

Glucose repression in *Saccharomyces cerevisiae*

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One sentence summary: The role of Snf1 signaling in glucose repression and carbon metabolism in *Saccharomyces cerevisiae*.

ABSTRACT

Glucose is the primary source of energy for the budding yeast *Saccharomyces cerevisiae*. Although yeast cells can utilize a wide range of carbon sources, presence of glucose suppresses molecular activities involved in the use of alternate carbon sources as well as it represses respiration and gluconeogenesis. This dominant effect of glucose on yeast carbon metabolism is coordinated by several signaling and metabolic interactions that mainly regulate transcriptional activity but are also effective at post-transcriptional and post-translational levels. This review describes effects of glucose repression on yeast carbon metabolism with a focus on roles of the Snf3/Rgt2 glucose-sensing pathway and Snf1 signal transduction in establishment and relief of glucose repression.

Keywords: carbon metabolism; Snf1 signaling; carbon catabolite repression

INTRODUCTION

When glucose is accessible the yeast *Saccharomyces cerevisiae* prefers a fermentative metabolism despite presence of oxygen, and represses respiration, use of alternative carbon sources as well as gluconeogenesis (Klein, Olsson and Nielsen ¹998; Roland, Windericks and Thevelein ²002). This repressive effect of glucose is transmitted to the cellular machinery by interlinked regulatory interactions and signaling pathways. These coordinative molecular activities mainly exert their effects at the transcriptional level, but they are also operative at post-transcriptional and post-translational levels.

Since *S. cerevisiae* primarily prefers glucose as a carbon source, sensing of extracellular and metabolized glucose levels is important for coordination of yeast carbon metabolism. Yeast cells adjust diverse cellular activities according to glucose levels detected extra- and intracellularly. The Snf3/ Rgt2 signaling pathway is a sensory cascade present in yeast for detecting extracellular glucose levels (Kaniak et al. ²004). Through this pathway, the cell can sense extracellular glucose levels and use this to regulate glucose uptake, and hereby trigger glucose repression. The Snf1 protein kinase signaling is central to functionality of glucose repression and to balance cellular energy levels. Snf1 kinase has a dual role in glucose repression, both as an activator and as a repressor. High glucose concentrations render Snf1 inactive which leaves the transcription factor Mig1 non-phosphorylated and hence being present in the nucleus where it exerts repression, together with Ssn6/ Tup1 complex, of genes involved in the utilization of alternative carbon sources (Gancedo ¹998; Hedbacker and Carlson ²008). On the other hand, when glucose becomes limited Snf1 is active and phosphorylates Mig1 allowing release of glucose repression and expression of glucose-repressed genes. Beside its central role in regulating expression of glucose-repressed genes, Snf1 kinase has direct interaction with the transcriptional apparatus, and it has...
Figure 1. Snf3/ Rgt2 glucose-sensing pathway. Snf3/ Rgt2 glucose-sensing pathway dictates expression levels of hexose transporter (HXT) genes for optimal uptake of glucose at various concentrations.

been implicated in chromatin modification (Kuchin, Treich and Carlson 2000). Moreover, as a part of its role in energy homeostasis Snf1 regulates metabolic enzymes involved in fatty acid metabolism and carbohydrate storage as well as a role affecting GCN4 translation and hence amino acid biosynthesis (Usaite et al. 2009; Hedbacker and Carlson 2010; Zhang et al. 2011).

Snf1 is the yeast AMP-activated kinase (AMPK), a regulatory kinase that is highly conserved in eukaryal cells. Understanding its function and regulation is therefore of broad and general interest, and much knowledge about AMPK has been acquired through the use of S. cerevisiae as a model organism (Petranovic and Nielsen 2008; Petranovic et al. 2010). Understanding glucose repression is, however, also of utmost importance for the development of biotechnological processes where it is desirable to redirect the carbon fluxes towards products of interests (Chen and Nielsen 2013; Dai et al. 2015; Li and Borodina 2015). Due to the high relevance of glucose repression in yeast, we therefore here review key pathways involved in this complex process in yeast.

Snf3/Rgt2 signaling

Snf3/Rgt2 signaling pathway mainly senses varying concentrations of available glucose in the environment. The Snf3 and Rgt2 sensors belong to the HXT (HeXose transporters) gene family together with the Hxt1–17 and Gal2 proteins that all but Hxt12 can transport glucose (and other hexoses) but each with a different affinity for glucose (Wieczorke et al. 1999). Although structurally similar to hexose transporters, Snf3 and Rgt2 cannot transport glucose (Ozcan, Dover and Johnston 1998). Snf3 senses low levels of extracellular glucose, while Rgt2 detects high levels of the sugar (Ozcan and Johnston 1999; Ozcan 2002). Intracellular signals generated upon detecting accessible amounts of glucose coordinate transcriptional regulation and expression of Hxt proteins (Fig. 1). Low-affinity transporters, such as Hxt1, are expressed and activated when glucose is abundant while under such conditions expression of high-affinity transporters, such as Hxt7, are repressed (Ozcan 2002). Snf3 and Rgt2 are also likely to sense internal-to-external ratio of glucose concentrations to adjust glucose uptake and maintain intracellular glucose homeostasis (Karhumaa, Wu and Kielland-Brandt 2010). Regulation of transcriptional activity through the Snf3/Rgt2 pathway allows S. cerevisiae to finely coordinate glucose uptake in response to environmental availability of this hexose sugar. When extracellular glucose is sensed by Snf3 and Rgt2 transmembrane proteins, the membrane-attached type I casein kinases Yck1 and Yck2 are activated. These active kinases are required for degradation of Mth1 and Std1, two paralogous regulatory proteins recruited to the plasma membrane (Schmidt et al. 1999; Moriya and Johnston 2004). Although Mth1 and Std1 were thought to be directly phosphorylated by Yck1/2 kinases for degradation, more recent data show that Mth1 is degraded in the nucleus independent of Yck1/2 localization (Pasula et al. 2010). So, according to this finding the glucose sensors transmit the glucose signal to a yet unidentified protein to promote phosphorylation and degradation of Mth1. Upon phosphorylation, Mth1 and Std1 are targeted for ubiquitination and proteosome degradation (Spielewoy et al. 2004). Furthermore, when glucose is abundant, Mig1 represses MTH1 expression to maintain glucose repression of the HXT genes. In contrast, as Std1 is being degraded its expression is increased to ensure efficient expression of the HXT genes when glucose is exhausted (Kim and Johnston 2006). Upon degradation of Mth1 and Std1, protein kinase A hyperphorylates and dislodges Rgt1, transcriptional repressor of glucose-induced genes, from DNA (Palomino, Herrero and Moreno 2006). Glucose-induced translocation of PKA to the nucleus allows hyperphosphorylation of Rgt1 (Griffioen et al. 2000; Kim and Johnston 2006; Roy et al. 2013, 2014). This allows for expression of
The Snf1 protein kinase is central player in glucose repression pathway. The Snf1 protein kinase regulates glucose repression at transcriptional level by activating or inactivating expression of gluconeogenic genes and genes involved in respiration. Depletion of glucose renders Mth1 and Std1 available for Rgt1 interaction, which conceals PKA phosphorylation sites on Rgt1 and as a result the repressor remains bound to promoters suppressing expression of HXT genes when glucose is unavailable (Flick et al. 2003). Snf1 phosphorylation of Rgt1 triggers the repressor activity of Rgt1 and its propensity to bind DNA (Palomino, Herrero and Moreno 2006). This interaction between Rgt1 and Snf1 kinase is critical for graded derepression of HXT expression and plays an important role in overall glucose repression.

SNF1 signaling

When glucose in the environment is exhausted, yeast cells switch their metabolism from fermentation to respiration, and activate mechanisms and components for utilization of alternative carbon sources. This usually occurs in the late exponential phase of a batch culture, where the cells are often referred to as being ‘derepressed’. Snf1 plays a central role in this metabolic shift by regulating a range of repressors and activators. Availability of glucose regulates activity of this central player in glucose repression. During growth on optimal glucose levels, Snf1 is inactive and excluded from the nucleus. This allows for a major downstream target of Snf1 the transcription repressor Mig1 to be non-phosphorylated and in the nucleus. Conversely, a drop in the glucose concentration (to about 0.2%) activates Snf1 which in turn phosphorylates and deactivates Mig1 relieving glucose repression (Fig. 2) (Piskur and Compagno 2014).

The yeast Snf1 is a widely conserved serine/threonine kinase in eukaryotes required for cellular energy homeostasis. Like the mammalian AMPK, Snf1 kinase complex in S. cerevisiae has a heterotrimeric structure with an alpha catalytic subunit (Snf1), a gamma regulatory subunit (Snf4) and one of three beta subunits (Sip1, Sip2, Gal83) (Carlson, Osmond and Botstein 1981; Amodeo, Rudolph and Tong 2007). When glucose levels are high, Snf1 kinase complex is inactive due to autoinhibition as a result of interaction between the N-terminal catalytic domain and C-terminal regulatory domains of Snf1 (Celenza and Carlson 1989; Jiang and Carlson 1996; Ludin, Jiang and Carlson 1998; Lefebvre et al. 2003). Low glucose concentrations remove this autoinhibition and promote interactions between Snf4 regulatory subunit and Snf1 catalytic subunits. Additionally, phosphorylation of the conserved residue at Thr^{210} is also required to activate Snf1 (McCarty and Schmidt 2001). In contrary to AMPK, Snf1 is not regulated by AMP but by ADP, which ensures a direct link between energy metabolism and this key regulator (Mayer et al. 2011).

Sak1, Elm1 and Tos3 are three protein kinases known to phosphorylate Thr^{210} in the Snf1 activation loop. These upstream kinases have overlapping functions since only deletion of all three abolishes Snf1 activation (Hong et al. 2003; Nath, McCartney and Schmidt 2003; Sutherland et al. 2003). So far, there has not been a report on how the glucose signal regulates the activating kinases of Snf1. Although each activating kinase contributes differently under different carbon source availability, Sak1 has the most stable interaction with Snf1; it is suggested to be the major activating kinase at conditions of growth on alternative carbon sources. The beta subunits also provide specificity for a particular upstream activating kinase under different conditions (McCarty, Rubenstein and Schmidt 2005). The three scaffolding (beta) subunits also regulate localization of Snf1 kinase. Sip1 directs Snf1 to vacuoles, while Sip2 keeps the enzyme in the cytoplasm and Gal83 play a role in nuclear localization of Snf1 (Vincent et al. 2001; Hedbaeker, Hong and Carlson 2004). Each subunit has been indicated to have a distinct yet overlapping role in regulation of transcription and cellular metabolism. For example, Gal83 and Sip2 both play a major role in activating gluconeogenic genes and genes involved with the glyoxylate cycle while Sip1 is mainly involved in the repression of genes associated with nitrogen metabolism (Zhang, Olsson and Nielsen 2010).

Another level of control is dephosphorylation of Snf1, which is carried out by Glc7/ Reg1 phosphotases (PF) (Feng et al. 1991; Tu and Carlson 1995). This level of control has been hypothesized to be the main regulator of Snf1 activity since phosphorylation of Snf1 by upstream kinases (Sak1, Elm1 and Tos3) has not been
Transcriptional effects on carbon metabolism

Upon activation, Snf1 kinase interacts with a number of transcription factors, activating some while suppressing others. Mig1 transcriptional repressor is a major downstream target of Snf1 phosphorylation. When phosphorylated by Snf1, this transcription repressor is deactivated and released from DNA allowing expression of glucose-repressed genes, mainly genes for utilization of alternative carbon sources. Mig1 mediates suppression of glucose-repressed genes together with the general repressor complex Smp6/Tup1 (Treitel and Carlson 1995; Lutfiyaa et al. 1998). Mig1 also interacts with Hxx2 to suppress glucose-induced genes. Besides its metabolic role as glucose, kinase Hxx2 also affects transcriptional regulation of glucose-repressible genes. When glucose is abundant Hxx2 interacts with Mig1 at Ser311, a site that is also targeted by Snf1 for phosphorylation (Ahuazti et al. 2007; Peláez, Herrero and Moreno 2010). By occupying this site, Hxx2 prevents Snf1 phosphorylation and hence removal of Mig1 from the nucleus. Furthermore, subsequent data suggest that Hxx2 is phosphorylated and dephosphorylated at Ser14 by Snf1 and Reg1/Glc7, respectively. Phosphorylation of Hxx2 prevents its nuclear localization and hence its interaction with transcription factors (Fernández-Garcia et al. 2012).

Cat8 is another transcription factor regulated by Snf1 activation and required for gluconeogenesis and survival on alternative carbon sources (Fig. 2). Snf1 controls activity of this transcription factor at two levels. While removal of Mig1 repression by Snf1 allows for upregulation of CAT8 expression, Snf1 phosphorylation of Cat8 triggers its activation (Hedges, Proft and Entian 1995; Randez-Gil et al. 1997). Cat8 derepresses target genes by binding to carbon source-responsive elements (CSREs) in upstream regions of these genes (Young et al. 2003; Roth, Kumme and Schüller 2004). Key gluconeogenic genes as well as genes involved in the glyoxylate cycle and utilization of non-fermentable carbon sources, including FBP1, MLS1 and ICL1, depend on Cat8 for their transcriptional regulation (Randez-Gil et al. 1997; Tachibana et al. 2007; Biddick, Law and Young 2008; Weinhandl et al. 2014). Recently, Snf1 was identified as a transcription factor also involved in regulation of gluconeogenesis and the glyoxylate cycle, but it is not known if Snf1 regulates this transcription factor (Tangosombativich et al. 2015).

Another major yet indirect target of Snf1 is the Adr1 transcriptional activator. Under glucose-depleted conditions, Adr1 is important for ethanol utilization and fatty acid metabolism (Fig. 2). Adr1 activity is triggered by Snf1-mediated dephosphorylation and also Snf1 regulates chromatin binding of Adr1 when glucose is scarce (Young, Kacherovsky and Van Riper 2002; Schüller 2003; Ratnakumar et al. 2009; Turcotte et al. 2010). Under repressing conditions though Reg1/Glc7 phosphatases inhibit chromatin binding of Adr1 (Dombek, Kacherovsky and Young 2004). Moreover, Adr1 affects DNA binding of Cat8 (Tachibana et al. 2005; Biddick, Law and Young 2008). Like Cat8, Adr1 also binds to CSREs, and in fact they both target key genes for derepression. For example, Adr1 and Cat8 trigger ADH2 transcription synergistically by binding at the upstream activation sites (Verdone et al. 2002; Tachibana et al. 2005). This binding is required for maximal expression of the ADH2 gene product of which, alcohol dehydrogenase 2, is glucose repressed and required for ethanol catabolism (Walther and Schüller 2001). ACS1, acetyl CoA synthase, is another locus which complete derepression, requires Adr1 and Cat8 working synergistically (Kratzer and Schüller 1997). Adr1 coordinates metabolic activities mainly important for acetyl-CoA and NADH generation from alternative carbon sources, such as lipids (Young et al. 2003). Transcription of FOX2, a multifunctional enzyme involved in fatty acid degradation, also depends on Adr1 (Ratnakumar and Young 2010; Turcotte et al. 2010). Besides coordination of transcriptional factors, Snf1 regulates gene expression by chromatin remodeling. Upon glucose depletion, Snf1 kinase activation of Cat8 and Adr1 plays a role in chromatin remodeling for proper expression of glucose-repressed genes (Agricola et al. 2004; Tachibana et al. 2005). For example, Adr1 restructures the promoter of the ADH2 gene to ensure proper transcriptional activity (Di Mauro 2000; Verdone et al. 2002). Moreover, Snf1 mediates chromatin restructuring also directly via Gcn5 acetyltransferase, as in the case of ADY2 glucose-repressed gene (Abate et al. 2012). Snf1 directly interacts with and phosphorylates the histone acetyltransferase Gcn5 and triggers its histone acetyl transferase activity (Liu, Xu and Kuo 2010). Gcn5-mediated acetylation is critical for transcriptional activation of many stress-responsive genes. For example, binding of Adr1 activation sites depends on the acetylation state of nucleosomes (Verdone et al. 2002). Another way Snf1 exerts its effects on transcriptional activity is by directly interacting with RNAI-pol holoenzyme. In response to glucose limitation, Snf1 kinase physically interacts and phosphorylates the holoenzyme and hereby triggers the transcription process (Kuchin, Treich and Carlson 2000; Young et al. 2012).

Post-transcriptional and translational effects on metabolism

Dynamic interactions of Snf1 at post-transcriptional and post-translational levels are important for Snf1’s role in balancing cellular energy levels when conditions are not favored. Snf1 achieves energy recalibration by inactivating energetically expensive cellular processes, such as amino acid and lipid biosynthesis, and meanwhile by upregulating programs, such as fatty acid oxidation, that generate energy. It is important to ensure coordinated regulation of carbon and nitrogen metabolism (Redeker and Færøgaard 2014), and under glucose starvation conditions Snf1 downregulates amino acid biosynthesis by inhibiting transcription and translation of GCN4 (Fig. 3). Deletion of SNF1 or inactivation of its kinase activity interestingly reveals significant induction in expression of genes mainly controlled by Gcn4 and required for amino acid generation (Shira et al. 2008; Zaman et al. 2009). On the other hand, however, Snf1 has also been implicated in promoting translation initiation and activation of Gcn4 by two different mechanisms depending on
Figure 3. The Snf1 protein kinase regulates glucose repression at post-transcriptional and post-translational level. Prominent components of metabolic activity are direct targets of Snf1 kinase activity.

CONCLUSIONS

Glucose repression involves regulation of a multitude of genes and proteins involved in carbon source utilization and energy generation, and Snf3/Rgt2 sensors and the Snf1 kinase are important for this mechanism. Since yeast cells adjust molecular and cellular activities in response to levels of available glucose, integrating the glucose signal to carbon metabolism is highly regulated. Optimal uptake of glucose starts with the induction of the Snf3/Rgt2 pathway that upregulates expression of hexose transporters best suited for the concentration of glucose in the environment. Snf1 plays a pivotal role in orchestrating the effects of glucose on carbon metabolism. Inactive Snf1, in presence of glucose, mediates transcriptional repression of a multitude of genes including gluconeogenic genes, genes involved in respiration and utilization of non-fermentable carbon sources. Conversely, once activated upon glucose limitation Snf1 phosphorylates a number of proteins to mediate glucose derepression and activation of mechanisms required for energy generation from alternative carbon sources.

Although studies done so far indicate highly interactive and intricate roles Snf1 plays in regulating glucose repression and its effect on carbon metabolism, still much remains to be elucidated; for example, it is not known how Snf1 is inactivated in response to presence of excess glucose, and how Snf1 kinase interacts with other (known and unknown) regulators to control glucose repression.

Conflict of interest. None declared.

REFERENCES


McCartney RR, Schmidt MC. Regulation of Snf1 kinase. Activation requires phosphorylation of threonine 210 by an


Treitel MA, Carlson M. Repression by SSN6-TUP1 is directed by MIG1, a repressor/activator protein. P Natl Acad Sci USA 1995; 92:3132–6.


Young ET, Kacherovsky N, Van Riper K. Snf1 protein kinase regulates Adr1 binding to chromatin but not transcription activation. *J Biol Chem* 2002;277:38095–103.