Chronological Lifespan in Yeast Is Dependent on the Accumulation of Storage Carbohydrates Mediated by Yak1, Mck1 and Rim15 Kinases

Lu Cao, Yingzhi Tang, Zhenzhen Quan, Zhe Zhang, Stephen G. Oliver, Nianshu Zhang

Cambridge Systems Biology Centre and Department of Biochemistry, University of Cambridge, Sanger Building, United Kingdom

Abstract

Upon starvation for glucose or any other macronutrient, yeast cells exit from the mitotic cell cycle and acquire a set of characteristics that are specific to quiescent cells to ensure longevity. Little is known about the molecular determinants that orchestrate quiescence entry and lifespan extension. Using starvation-specific gene reporters, we screened a subset of the yeast deletion library representing the genes encoding ‘signaling’ proteins. Apart from the previously characterised Rim15, Mck1 and Yak1 kinases, the SNF1/AMPK complex, the cell wall integrity pathway and a number of cell cycle regulators were shown to be necessary for proper quiescence establishment and for extension of chronological lifespan (CLS), suggesting that entry into quiescence requires the integration of starvation signals transmitted via multiple signaling pathways. The CLS of these signaling mutants, and those of the single, double and triple mutants of \textit{RIM15}, \textit{YAK1} and \textit{MCK1} correlates well with the amount of storage carbohydrates but poorly with transition-phase cell cycle status. Combined removal of the glycogen and trehalose biosynthetic genes, especially \textit{GSY2} and \textit{TPS1}, nearly abolishes the accumulation of storage carbohydrates and severely reduces CLS. Concurrent overexpression of \textit{GSY2} and \textit{TSL1} or supplementation of trehalose to the growth medium ameliorates the severe CLS defects displayed by the signaling mutants (\textit{rim15Δyak1Δ} or \textit{rim15Δmck1Δ}). Furthermore, we reveal that the levels of intracellular reactive oxygen species are cooperatively controlled by Yak1, Rim15 and Mck1, and the three kinases mediate the \textit{TOR1}-regulated accumulation of storage carbohydrates and CLS extension. Our data support the hypothesis that metabolic reprogramming to accumulate energy stores and the activation of anti-oxidant defence systems are coordinated by Yak1, Rim15 and Mck1 kinases to ensure quiescence entry and lifespan extension in yeast.

Author Summary

Calorie restriction improves healthy lifespan in all the organisms from yeast to mammals. However, our knowledge of the underlying mechanisms is still limited. The budding yeast
naturally experiences calorie restriction when glucose in the rich medium is exhausted and cells start to consume the fermentation products before entering the stationary phase. Here, we demonstrate that the key for yeast cells to survive in the stationary phase is to accumulate sufficient storage carbohydrates (both trehalose and glycogen) during the transition phases. This accumulation requires the integration of starvation signals transduced from multiple signaling pathways, including those activated by the inhibition of the major nutrient sensors (TOR/PKA), the energy-sensing complex (SNF1/AMPK), and the cell wall integrity pathway. We have also shown that the levels of intracellular reactive oxygen species and the population size are limited by those starvation signals downstream of TOR. Therefore, our data suggest that metabolic reprogramming to increase energy stores, anti-oxidant defence systems and population control are cooperatively activated by a set of key signaling proteins to ensure longevity in eukaryotic cells.

**Introduction**

Studies in invertebrates and rodents have consistently shown that dietary intervention mimicking calorie restriction (CR) or mutations in nutrient and growth signalling pathways can increase longevity by 30–50%, accompanied by reduced or delayed morbidity in most cases [1]. Among the nutrient signalling pathways, the conserved TOR pathway regulates lifespan from simple eukaryotes to mammals [2–3]. Active signalling through TOR limits lifespan in budding yeast, nematodes, fruit flies, and mice [3]. Feeding mice with the TOR inhibitor rapamycin, even late in life, extends lifespan, representing the first pharmacological anti-aging regime in mammals [4]. However, rapamycin treatment has many side effects, including metabolic dysregulation, proliferative defects in the hematopoietic lineage, and others [5]. The TOR pathway controls many aspects of cell physiology, promoting ribosome biogenesis, translation and thus cell growth and proliferation, but also inhibiting autophagy and the stress response [6–7]. It remains unclear which aspects of TOR signalling contribute most significantly or specifically to aging and lifespan regulation [8].

In budding yeast, lifespan is classified as replicative lifespan (RLS), defined as the number of daughter cells a mother can produce before senescence, and chronological lifespan (CLS), defined as the period of time that non-dividing cells remain alive in stationary phase [9]. Down-regulation of TOR activity extends both RLS and CLS. Deletion of the Sch9 kinase, the yeast homolog of mammalian S6K1 and a downstream effector of the TORC1 complex [10], significantly extends CLS [11]. Two mechanisms, probably acting in parallel, have been proposed to account for CLS extension in yeast cells with compromised TOR. First, TOR1 deletion enhances mitochondrial respiration. Mitochondrial ROS produced in exponentially-growing tor1Δ or sch9Δ cells provides an adaptive hormetic signal to activate the stress response dependent on Msn2/4 and Gis1, resulting in reduced levels of ROS in stationary phase cells and their elevated survival [12]. This mtROS-activated hormesis and longevity extension also involves Rph1-dependent epigenetic silencing at subtelomeric heterochromatin via Tel1 and Rad53, homologs of the mammalian DNA damage response kinases ATM and Chk2 [13]. It is proposed that activation of mitochondrial respiration above a threshold level to accumulate sufficient nutrient stores (storage carbohydrates) is essential to stress resistance and CLS extension [14].

CLS extension as a result of tor1Δ or sch9Δ deletion is also dependent on the Rim15 kinase (analogous to the Greatwall kinase) and its downstream effectors, Msn2/4 and Gis1, to activate stress response [15]. Nutrient starvation or TORC1 inhibition activates Rim15 [16], which in
turn, via the yeast endosulfines Igo1/Igo2, prevents newly expressed mRNAs from decapping and degradation [17] and preserves its effectors in a phosphorylated (active) state by inhibiting PP2A−Cdc55 phosphatase activity [18]. A few lines of evidence suggest that other aspects of the nutrient-sensing pathways are involved in CLS regulation. Firstly, in response to severe calorie restriction (CR), the yeast Fkh1 and Fkh2, orthologs of metazoan FOXO transcription factors, regulate chronological lifespan and oxidative stress response together with the anaphase-promoting complex [19]. How nutrient starvation signals are transmitted to Fkh1 and Fkh2 is not clear. Secondly, we have identified Yak1, the yeast homolog of the mammalian DYRKs, as the kinase acting in parallel with Rim15 to activate stress response dependent on Msn2/4 and Gis1 in TORC1-inhibited cells [20]. Recently, we have shown that the yeast GSK-3 homolog Mck1 is a key regulator of quiescence entry and Mck1 acts in parallel to Rim15 to activate starvation-induced gene expression, the acquisition of stress resistance, the accumulation of storage carbohydrates, and the extension of CLS [21]. Mck1 is necessary to regulate ribosome and tRNA synthesis [22] and to mediate very long chain fatty acid synthesis and autophagy [23] in TORC1-inhibited cells, suggesting that the function of Mck1 may be regulated by the TOR pathway. These studies indicate that starvation-induced stress response, one of the major mechanisms of modulating CLS, involves a more complex signalling network than previously thought.

Here, using reporters whose expression is induced by starvation, we screened a subset of the deletion library representing the ‘signaling’ mutants and revealed that the stress response, quiescence establishment and CLS extension require the integration of multiple signals, including those transduced from the TOR/PKA, SNF1/AMPK and the cell wall integrity (CWI) pathways. We demonstrated that starvation-induced stress resistance and CLS extension in WT or tor1Δ cells is dependent on the accumulation of both glycogen and trehalose, mediated by the Rim15, Yak1 and Mck1 kinases. The three kinases also cooperate to control the levels of intracellular reactive oxygen species as well as the population entering the stationary phase, therefore increasing the storage carbohydrates and the capacity to defend against oxidative stress in single cells. These findings suggest that metabolic reprogramming to increase energy stores and the activation of the anti-oxidant defence systems are the primary objectives of the anti-aging signaling network at a time of nutrient scarcity.

Results

The SNF1/AMPK and the cell wall integrity (CWI) pathways are necessary for starvation-induced gene expression and CLS extension

Wei et al. [15] have predicted that other factors than Rim15 are involved in regulating the stress response and lifespan extension by calorie restriction. To facilitate the automated identification of these factors regulating the stress response, the deletion mutants of the 272 genes in the yeast genome that encode the majority of the ‘signaling’ molecules were screened using two starvation-induced gene reporters, pHSP12-HSP12-VFP and pSSA3-RFP, following the procedures described in Fig 1A. Starvation-induced expression of the two reporters have been shown to be dependent on Msn2/4 and Gis1 [21]. In the SSA3 promoter, we also identified a heat shock element (HSE, 5′-NGAANN5NGAANN5NGAAN-3′), which is targeted by the heat shock factor, Hsf1 [24]. Decreasing the level of Hsf1 by using a DAmP strain [25] or mutating the HSE in the SSA3 promoter (see Materials and Methods) significantly reduced the levels of RFP (S1A and S1B Fig), suggesting that pSSA3-RFP expression induced by starvation is also regulated by Hsf1. Mutating the HSE in the SSA3 promoter completely abolished the expression of RFP in the msn2/4Δgis1Δ mutants (S1B Fig). These data confirmed previous observations that Hsf1, Msn2/4 and Gis1 cooperate to regulate starvation-induced stress response [20,26].
In comparison to wild-type cells, 45 mutants (about 16%) displayed significant changes of pSSA3-RFP and/or pHSP12-HSP12-VFP levels (Fig 1B, *p* < 0.05). The negative regulators, exhibiting higher levels of the fluorescent reporters in their mutants (Fig 1B), are subunits of C-terminal domain kinase 1 (CTK1 and CTK3), components of PP2A complex (PPM1 and RTS1), PP2A-like phosphatase (PPG1) and PP2C (PTC1). In contrast, besides the previously reported RIM15, YAK1, and MCK1 (see the introduction), deletion of genes involved in a number of pathways caused a significant decrease of starvation-induced gene expression. These include genes implicated in the cell wall integrity pathway (PKH1, RHOS, BCK1, SLT2 and RLM1), in the SNF1/AMPK complex (SNF1, TOS3 and SAK1), in the PKA (PDE2 and TPK1) and the MAPK pathway governing meiosis (IME2 and STE11), in cell cycle control (SKM1, SIC1 and MIH1), and a couple of kinases whose expression is induced by mild-heat stress (IKS1) or by carbon limitation (RGI2). As compared to WT cells, the expression of pSSA3-RFP in the bck1Δ mutants was induced to a similar level in the first 48 hours (Fig 1B) but its accumulation was severely decreased, to a level similar to that in the slt2Δ cells when assayed on agar plates (see the red box in Fig 1B). More mutants (37) displayed decreased expression of the reporters than those (8) showing increased levels (Fig 1B).
suggesting that activation of starvation-specific gene expression may involve the integration of signals transduced by multiple pathways.

Apart from RIM15, YAK1, and MCK1 (see next section), deletion of 23 genes led to a severe decrease of pSSA3-RFP expression (>2-fold, boxed in green in Fig 1B). To discover whether these mutants displayed other defects associated with the transition phases, we also analyzed their FACS profiles at the late-exponential phase (11h) and during the transition to stationary phase (24h; Table 1), the accumulation of glycogen and trehalose at early stationary phase (72h, Table 1) and their ability to exit from quiescence during the stationary phase (Fig 2A).

As compared to WT cells, a number of mutants, including bni4Δ, rho5Δ, rhr2Δ, sic1Δ and pde2Δ, exhibited a significantly higher proportion of budded (S/G2/M) cells at both late exponential and transition phases (compare 11h and 24h, Table 1), suggesting defects in G2/M transition or mitosis. The high budding index displayed by the slt2Δ or yck3Δ mutant at the late exponential phase decreased in the transition phase, whereas those of sbp1Δ, sak1Δ and ste11Δ increased dramatically, indicating that these signaling proteins regulate the cell cycle progression in a way dependent on the nutrient status. Previous cell sorting and FACS analyses [21]

Table 1. Budding index and storage carbohydrates accumulated in the transition phase.

<table>
<thead>
<tr>
<th>Name</th>
<th>Functional category</th>
<th>Gene function</th>
<th>S-G2-M cells (%)</th>
<th>Glycogen (μg/mg, 72h)</th>
<th>Trehalose (μg/mg, 72h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WT</td>
<td>-</td>
<td>-</td>
<td>40.9 34.5</td>
<td>10.0 ± 0.2</td>
<td>23.2 ± 1.1</td>
</tr>
<tr>
<td>PKH1</td>
<td>Cell wall integrity</td>
<td>Serine/threonine protein kinase</td>
<td>32 22.4</td>
<td>12.4 ± 0.7</td>
<td>22.9 ± 0.3</td>
</tr>
<tr>
<td>RHO5</td>
<td>Non-essential small GTPase</td>
<td>Serine/threonine MAP kinase</td>
<td>75.3 63.7</td>
<td>3.8 ± 0.2</td>
<td>6.2 ± 0.7</td>
</tr>
<tr>
<td>SLT2</td>
<td>-</td>
<td>Protein kinase for the activation of Snf1p</td>
<td>54.7 38</td>
<td>9.3 ± 0.3</td>
<td>21.8 ± 1.6</td>
</tr>
<tr>
<td>TOS3</td>
<td>SNF1 complex</td>
<td>Upstream kinase for the SNF1 complex</td>
<td>37.7 58.1</td>
<td>0.5 ± 0.1</td>
<td>9.5 ± 1.7</td>
</tr>
<tr>
<td>SAK1</td>
<td>-</td>
<td>AMP-activated S/T protein kinase</td>
<td>46.1 34.9</td>
<td>0.8 ± 0.1</td>
<td>0.6 ± 0.1</td>
</tr>
<tr>
<td>SNP1</td>
<td>PKA pathway</td>
<td>High-affinity cyclic AMP phosphodiesterase</td>
<td>63.4 67.7</td>
<td>6.6 ± 1.2</td>
<td>9.2 ± 0.4</td>
</tr>
<tr>
<td>PDE2</td>
<td>-</td>
<td>cAMP-dependent protein kinase catalytic subunit</td>
<td>48.8 50.3</td>
<td>8.0 ± 0.1</td>
<td>16.2 ± 0.7</td>
</tr>
<tr>
<td>SKM1</td>
<td>Cell cycle cytoskeleton</td>
<td>Member of the PAK family of serine/threonine protein kinases</td>
<td>38.7 54.7</td>
<td>9.8 ± 0.3</td>
<td>18.3 ± 1.4</td>
</tr>
<tr>
<td>SIC1</td>
<td>Cyclin-dependent kinase inhibitor (CKI)</td>
<td>65.6 53</td>
<td>11.1 ± 0.1</td>
<td>19.0 ± 0.6</td>
<td></td>
</tr>
<tr>
<td>MIIH</td>
<td>Protein tyrosine phosphatase</td>
<td>36.3 43.6</td>
<td>8.8 ± 0.3</td>
<td>19.5 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>TWF1</td>
<td>Twinfilin</td>
<td>34.3 36.2</td>
<td>11.1 ± 0.4</td>
<td>21.4 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>BNI4</td>
<td>Targeting subunit for Glc7p protein phosphatase</td>
<td>69.4 71.5</td>
<td>9.6 ± 0.1</td>
<td>15.8 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>STE11</td>
<td>MAPK pathway</td>
<td>Signal transducing MEK kinase</td>
<td>36.7 56.6</td>
<td>1.5 ± 0.3</td>
<td>12.0 ± 1.3</td>
</tr>
<tr>
<td>IME2</td>
<td>Serine/threonine protein kinase involved in activation of meiosis</td>
<td>38.5 47.8</td>
<td>10.5 ± 0.2</td>
<td>20.1 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>RHR2</td>
<td>Glycerol biosynthesis</td>
<td>Constitutively expressed DL-glycerol-3-phosphate phosphatase</td>
<td>70.5 81.4</td>
<td>2.3 ± 0.1</td>
<td>13.1 ± 0.7</td>
</tr>
<tr>
<td>INP54</td>
<td>Secretion, vacuole sorting and fusion</td>
<td>Phosphatidylinositol 4,5-bisphosphate 5-phosphatase</td>
<td>32.3 39.7</td>
<td>9.7 ± 0.3</td>
<td>21.0 ± 0.7</td>
</tr>
<tr>
<td>YCK3</td>
<td>Palmitoylated vacuolar membrane-localized casein kinase I isoform</td>
<td>79.4 50.2</td>
<td>6.7 ± 1</td>
<td>16.0 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>FAB1</td>
<td>1-phosphatidylinositol-3-phosphate 5-kinase</td>
<td>51.4 30</td>
<td>7.4 ± 0.3</td>
<td>18.9 ± 0.3</td>
<td></td>
</tr>
<tr>
<td>YIH1</td>
<td>Regulation of translation in response to glucose starvation</td>
<td>Negative regulator of elf2 kinase Gcn2p</td>
<td>53.5 47</td>
<td>13.1 ± 1.5</td>
<td>21.4 ± 2.0</td>
</tr>
<tr>
<td>SBP1</td>
<td>Protein that binds elf4G and has a role in repression of translation</td>
<td>40.6 62.1</td>
<td>2.7 ± 0.2</td>
<td>15.2 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>RGII</td>
<td>Unknown</td>
<td>Protein of unknown function</td>
<td>48.5 47.7</td>
<td>8.9 ± 0.4</td>
<td>19.1 ± 1</td>
</tr>
<tr>
<td>IKS1</td>
<td>Protein kinase of unknown cellular role</td>
<td>32.5 35</td>
<td>10.6 ± 0.5</td>
<td>22.5 ± 1.5</td>
<td></td>
</tr>
</tbody>
</table>

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Chronological Lifespan Is Dependent on Storage Carbohydrates

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revealed three distinct populations in WT cell cultures in transition phases: small daughter cells (G₀), larger daughter or unbudded mother cells (G₁) and the budded cells (S/G₂/M, S2 Fig). In the transition-phase cultures of sbp1Δ, sak1Δ or rhr2Δ mutants, an extra population representing a 3C DNA content was evident from their FACS profiles (encircled in red, S2 Fig), suggesting defects of cytokinesis or cell separation when these mutants were growing on non-fermentable carbon sources. The majority of these signaling mutants showed a reduced CFU when compared to WT cells over a period of 21 days (Fig 2A). The relative CFU (at day 14) of these mutants seems to correlate well with the amount of trehalose (R² = 0.43; Fig 2B) or the total amount of trehalose and glycogen (R² = 0.39, Fig 2C), less well with glycogen (R² = 0.27, Fig 2D), but very poorly with the ratio of 1C cells (G₀/G₁) in the transition phase (R² = 0.015; Fig 2E), suggesting that signalling to accumulate energy stores, especially trehalose, may be important to long-term survival.

**Fig 2.** CLS of the signaling mutants is well correlated with the amount of storage carbohydrates. 2A: Relative CFU of WT and ‘signaling’ mutants at 7, 14 and 21 days normalised to that at day 0. Day 0 data is collected after cells were grown in YPD for three days to early stationary phase. 2B, 2C, 2D and 2E: Correlation coefficient (R) between relative CFU (at day 14) and trehalose (2B), the sum of trehalose and glycogen (2C), glycogen (2D) or the ratio of G₀/G₁ (1C) cells at 24h (2E).

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Many of the yeast proteins implicated in signaling pathways that are required to activate starvation-induced gene expression have mammalian orthologs. Yak1 belongs to the group of dual-specificity tyrosine phosphorylation-regulated kinases (DYRKs)\[27\]. Upon TORC1 inhibition, Yak1 translocates to the nucleus to activate the transcription of Msn2/4 targets \[20,28\] and to down-regulate the expression of ribosomal protein genes \[29\]. The GSK-1 homolog Mck1 was recently shown to act in parallel to the Rim15 kinase to enable the acquisition of a number of quiescence-related characteristics and CLS extension \[21\]. Previously, PDR5 was removed from WT, and the rim15\Delta, mck1\Delta and rim15\Deltamck1\Delta mutants in order to find how the proteasome function influences starvation-induced gene expression \[21\]. To reveal the genetic relationship between YAK1 and RIM15 or MCK1 in starvation-induced stress response, the levels of pHSP12-HSP12-VFP and pSSA3-RFP reporters were determined in the single, double and triple mutants of YAK1, RIM15 and MCK1, which were generated in the same genetic background (pdr5\Delta). The rim15\Deltamck1\Delta double mutants were included for comparison. As compared to the single mutants, the expression of pHSP12-HSP12-VFP and pSSA3-RFP was dramatically reduced in the rim15\Deltayak1\Delta or yak1\Deltamck1\Delta double mutants, albeit to a lesser degree than that seen in the rim15\Deltamck1\Delta deletants (Fig 3A). Deletion of all three genes completely abolished the expression of both reporters (Fig 3A). These data suggest that Yak1 activates starvation-induced gene expression in parallel or compensatory pathways to those of Rim15 and Mck1. To further examine the physiological implications of the above findings, stress resistance exhibited by early stationary-phase cells (grown in YPD for 3 days) was monitored. As shown in Fig 3B, the yak1\Delta single mutants display severe defects in response to heat shock and moderate sensitivity to oxidative stress as compared to WT cells. The rim15\Deltayak1\Delta or yak1\Deltamck1\Delta double mutants, similar to the rim15\Deltamck1\Delta mutants, recapitulate the heat shock sensitivity of the gis1\Dmsn2/4\Delta triple mutants and display stronger defects in response to oxidative stress than the latter, indicating that the three kinases cooperate to control the acquisition of stress resistance during the transition into stationary phase.

The cellular content of storage carbohydrates (trehalose and glycogen) was also determined after 3 days in YPD. As compared to that observed in wild-type cells, accumulation of trehalose was severely reduced in the yak1\Delta mutants (Fig 3C). In mutants bearing double deletions of YAK1 and RIM15 or YAK1 and MCK1, the amount of trehalose was lower than that in the single kinase mutants, similar to what was seen in the rim15\Deltamck1\Delta mutants. The accumulation of trehalose was almost abolished in the rim15\Deltayak1\Deltamck1\Delta triple mutant (Fig 3C), indicating that the three kinases may act in parallel and/or compensatory pathways to enable trehalose accumulation. In contrast to the severe decrease of glycogen seen in the rim15\Delta or mck1\Delta deletion cells, deletion of YAK1 led to a dramatic increase of glycogen (Fig 3C), a phenotype which has been reported previously (Wilson et al., 2002). YAK1 deletion led to a significant increase of glycogen in the mck1\Delta cells but only a marginal increase in the rim15\Delta or rim15\Deltamck1\Delta mutants (Fig 3C), suggesting that glycogen hyper-accumulation due to YAK1 deletion is predominantly mediated through the Rim15 pathway.

After 3 days of growth in YPD, the number of colonies formed by the yak1\Delta cell culture was increased by \(~40\%\) compared to that by the WT culture (Fig 3D). A similar increase was also seen from those produced by the rim15\Delta or mck1\Delta mutants (Fig 3D). Further deletion of RIM15 or MCK1 from the yak1\Delta mutant increased the CFU by \(~100\%\), to a similar extent to that formed by the rim15\Deltamck1\Delta double mutant (Fig 3D), suggesting that Yak1 acts together with Rim15 or Mck1 to limit the population entering the stationary phase. Cell division in budding yeast is extremely asymmetric under nutrient limitations (Lord and Wheals, 1981).
We have previously demonstrated that, in the WT cell culture, FACS can be used to differentiate the new daughter cells (Gd) from those having grown to the size of their mothers (G1) and those having entered into the S phase and mitosis (S-G2-M cells) ([21], S2 and S3 Figs). In the rim15Δmck1Δ double mutant culture, the G1 population cannot be discriminated from Gd cells by FACS [21] and the size of Gd/G1 or S-G2-M cells is significantly decreased (Fig 3E and 3F), indicating that Mck1 and Rim15 function to maintain the size threshold at the G1/S transition to restrict the population growth. The median and size distribution of the Gd/G1 or S-G2-M cells in the yak1Δ culture is moderately reduced as compared to those in the WT culture (Fig 3E and 3F). Removal of YAK1 from the rim15Δ mutant leads to even smaller Gd/G1 or S-G2-M cells (Fig 3E and 3F) and coalescence of the two populations in the FACS profile (S3 Fig), similar to what was seen in the rim15Δmck1Δ mutants (Fig 3E and [21]).

Fig 3. Phenotypic analysis of the single, double and triple mutants of RIM15, YAK1 and MCK1. 3A: Expression levels of pHSP12-HSP12-VFP at 20h and of pSSA3-RFP at 48h in the above mutants. 3B: Heat and oxidative stress resistance displayed by WT and mutant cells grown for 3 days in YPD. 3C: Glycogen and trehalose accumulated in WT and mutant cells grown for 3 days in YPD. 3D: The number of colonies formed by WT and mutant cell cultures grown in YPD for 3 days. 3E: Median, 1st and 3rd quartiles of cell size of the Gd and G1 populations in the day 3 culture. 3F: Median, 1st and 3rd quartiles of cell size of the S-G2-M and >2C populations in the day 3 culture. At least 100,000 Gd/G1 and 15,000 >2C cells from each culture were scored. The pairwise comparisons between WT and each mutant in 3e and 3f reveal that all p values calculated from the t-test scores are less than 0.0001.

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YAK1 from the mck1Δ mutant marginally reduces the size of G₃/G₁ or S-G₂-M cells (Fig 3E and 3F) but significantly decreases the >2C population observed in the mck1Δ culture (S3 Fig). These data suggest that Yak1 may act together with Rim15 to regulate the size threshold for the G₁/S transition to control the population growth. The population increase seen in the yak1Δmck1Δ culture may be due to a combination of size control defects (Fig 3E) and the resolving of the multi-budded population (S3 Fig). These data suggest that Yak1, Mck1 and Rim15 kinases cooperate to regulate the accumulation of storage carbohydrates and the population entering the stationary phase.

To confirm that the accumulation of both trehalose and glycogen are necessary for exit from quiescence, GSY2, responsible for the majority (~90%) of the glycogen synthase activity in S. cerevisiae [31], was removed from the tps1Δ or tsl1Δ mutants. TPS1 encodes the synthase subunit of trehalose-6-P synthase/phosphatase (TPS/TPP) complex and its deletion results in loss of both TPS activity and trehalose biosynthesis [32]. TSL1 encodes a regulatory protein for TPS/TPP and removal of TSL1 has only minor effects on TPS/TPP activities and on trehalose biosynthesis [33]. The levels of trehalose and glycogen accumulated in WT and mutant cells were consistent with these observations (Fig 5A). The accumulation of trehalose was not changed in the gsy2Δ mutants, whereas a great increase of glycogen was seen in the tps1Δ cells (Fig 5A), suggesting that biosynthetic activity was directed towards glycogen when trehalose biosynthesis was compromised. Profound sensitivity to heat or mild sensitivity to oxidative stress was associated with tps1Δ, independent of GSY2 (Fig 5B); this agrees with previous observations that tps1Δ mutants showed hypersensitivity to various stresses [34–40]. Relative CFU formed by the stationary-phase tps1Δ cells was reduced to less than 5% by day 21, whereas those produced by the gsy2Δ or tsl1Δ deletants remained similar to that of the WT cells (Fig 5C). Further deletion of GSY2 from the tps1Δ cells (gsy2Δtps1Δ) exacerbates its CFU.
defects (Fig 5C). Deletion of GSY2 from the tsl1Δ mutant (gsy2Δtsl1Δ) also results in a mild CFU defect which was not observed in gsy2Δ or tsl1Δ single mutant (Fig 5C). Relative CFU at day 14 among WT and these mutants correlates poorly with glycogen (R² = 0.09, S4C Fig), very well with trehalose (R² = 0.73, S4D Fig), and best with the total amount of storage carbohydrates (R² = 0.88, S4E Fig). The majority of the tps1Δ or gsy2Δtps1Δ cells remained viable when they lost the ability to form colonies and these cells gradually become inviable (Fig 5D), further suggesting that failure to accumulate storage carbohydrates causes defects first in

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Fig 4. Chronological lifespan of the single, double and triple mutants of RIM15, YAK1 and MCK1 is well correlated with the accumulation of storage carbohydrates. 4A: Relative CFU measured over 21 days. 4B: Comparison between relative CFU and cell survival displayed by WT and mutant cultures at day 12. 4C, 4D and 4E: Correlation between relative CFU (at day 15) and total amount of storage carbohydrates (4C), trehalose (4D) or glycogen (4E). 4F: Correlation between relative CFU and the ratio of G₂/G₁ (1C) cells at 24h in YPD.

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quiescence exit and subsequently in cell survival. The $g_{sy2}\Delta tps1\Delta$ cells lost their viability more quickly than the $tps1\Delta$ mutants (Fig 5D). Put together, these data support that the accumulation of trehalose plays a dominant role in quiescence exit but glycogen storage contributes to long-term survival.

The accumulation of both storage carbohydrates is substantially decreased in the $rim15\Delta yak1\Delta$ or $rim15\Delta mck1\Delta$ double mutants (Fig 3C) and they were unable to exit from quiescence during mid-stationary phase (Fig 4A). To confirm that quiescence exit regulated by Rim15 and Yak1 or Rim15 and Mck1 is dependent on the accumulation of storage carbohydrates, we attempted (but failed) to remove both $RIM15$ and $YAK1$ or $RIM15$ and $MCK1$ from the $g_{sy2}\Delta tps1\Delta$ mutants. Instead, $GSY2$ and $TSL1$ were overexpressed in the $rim15\Delta yak1\Delta$ cells. Cells bearing the overexpression plasmids were grown in buffered SC medium [41] to avoid the adverse effect of acidification on CLS. After growth for 3 days, cells were washed and resuspended in sterile water for CFU assays to prevent cryptic growth observed for the $rim15\Delta yak1\Delta$ double mutants (Fig 4A). Concurrent expression of $GSY2$ and $TSL1$ in the $rim15\Delta yak1\Delta$ cells enhanced their resistance to heat stress (Fig 6A), increased the amount of glycogen and trehalose by ~2- and 3~4-fold respectively (Fig 6B), and significantly improved their capability to form colonies (Fig 6D) and their survival rate (S5B Fig). Concurrent overexpression of $GSY2$ and $TPS1$ in the $rim15\Delta yak1\Delta$ cells also...

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**Fig 5.** The accumulation of both trehalose and glycogen is necessary for quiescence exit. **5A:** Glycogen and trehalose levels determined in the $g_{sy2}\Delta$, $tps1\Delta$ and $tsl1\Delta$ single and the $g_{sy2}\Delta tps1\Delta$ and $g_{sy2}\Delta tsl1\Delta$ double mutants. **5B:** Heat and oxidative stress resistance displayed by the above mutants. **5C:** Relative CFU of the above mutants over 28 days. **5D:** Comparison between relative CFU and cell viability of the $tps1\Delta$ and $g_{sy2}\Delta tps1\Delta$ mutants over 28 days.

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enhanced the levels of glycogen and trehalose, albeit to a lesser degree than those seen in the same cells overexpressing GSY2 and TSL1 (Fig 6B). However, heat stress resistance is not improved (Fig 6A), CFU is only marginally increased (Fig 6D) and their survival rate remained the same as the same cells bearing the empty vectors (S5B Fig). The levels of trehalose and glycogen are increased in WT cells overexpressing GSY2/TPS1 or GSY2/TSL1 (Fig 6B). Stress resistance (Fig 6A), relative CFU (Fig 6C) or cell survival (S5A Fig) displayed by these cells is similar to those bearing the empty vectors. These data suggest that the accumulation of storage carbohydrates above a certain threshold is essential to enable stress resistance and CLS extension.

The accumulation of glycogen was marginally and that of trehalose significantly increased in the rim15Δmck1Δ mutants overexpressing GSY2 and TPS1, and to a lesser extent upon coordinate overexpression of GSY2 and TSL1 (Fig 6B). However, no enhanced stress resistance (Fig

Fig 6. The CLS defects in the rim15Δyak1Δ or rim15Δmck1Δ mutants are rescued by GSY2/TS L1 overexpression and/or trehalose supplementation. 6A and 6B: Stress resistance (6A) and storage carbohydrates (6B) accumulated in the rim15Δyak1Δ or rim15Δmck1Δ cells bearing the empty vectors, GSY2/TPS1 or GSY2/TSL1 overexpression plasmids. 6C, 6D and 6E: Relative CFU of WT (6C), the rim15Δyak1Δ (6D) and rim15Δmck1Δ (6E) mutants overexpressing GSY2/TPS1 or GSY2/TSL1. 6F, 6G and 6H: Supplementation of trehalose enhances the ability of WT cells to exit from quiescence (6F), ameliorates or rescues the CFU defects of the rim15Δyak1Δ (6G) and rim15Δmck1Δ (6H) cells. Cells were grown in YPD supplemented with 1% Trehalose from inoculation.

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and only marginal increase of CFU (Fig 6E) was observed in the rim15Δmck1Δ mutants overexpressing GSY2 and TPS1. On day 0, the number of colonies grown from the rim15Δmck1Δ culture is only around a third of those from the rim15Δyak1Δ or WT cultures. Viability tests revealed that the vast majority of the rim15Δmck1Δ cells (>60–70%) had died after three days of incubation in buffered SC medium (S5C Fig), a phenotype seen in rich medium only after 12 days (Fig 4B). Thus, deletion of RIM15 and MCK1 may lead to substantial cell death in poorer nutrient conditions. A moderate increase of storage carbohydrates is not sufficient to rescue this lethality.

Trehalose can be assimilated by actively-growing cells [14]. 1% trehalose was added into the growth medium from inoculation. Addition of trehalose mildly improved the CFU of WT cells in the stationary phase (Fig 6F), partially rescued the CFU defects exhibited by the rim15Δyak1Δ mutants (Fig 6G) and dramatically restored the relative CFU of the rim15Δmck1Δ mutants close to the WT levels (Fig 6H). These observations further confirmed that signaling to accumulate storage carbohydrates is crucial to CLS extension.

Rim15, Yak1 and Mck1 cooperate to control intracellular reactive oxygen species (ROS)

The accumulation of storage carbohydrates in the rim15Δyak1Δmck1Δ triple mutant or the gsy2Δtps1Δ double deletant is nearly abolished (Fig 3C and Fig 5A). However, the former lost their ability to exit from quiescence more quickly than the latter (compare Fig 4A and Fig 5C). Although both mutants displayed similar defects in resistance to heat shock (Fig 3B and Fig 5B), the rim15Δyak1Δmck1Δ mutants exhibited a more severe defect in their resistance to exogenous oxidant than the gsy2Δtps1Δ cells (Fig 3B and Fig 5B), indicating that the three kinases may cooperate to regulate the anti-oxidant defence systems to extend CLS. To confirm this, dihydrorhodamine 123 (DHR) was used to determine the levels of intracellular ROS in early stationary-phase cells (see Materials and Methods). As compared to WT, removal of any of the three kinase genes increased the levels of ROS significantly (see the p values listed below each mutant in Fig 7A). Among the three double mutants, only the rim15Δyak1Δ cells

![Fig 7. The levels of intracellular ROS in early stationary-phase cells are controlled by Rim15, Yak1 and Mck1. A: ROS levels determined in WT, the single, double and triple mutants of RIM15, YAK1 and MCK1. B: ROS levels detected in WT, the single and double mutants of GSY2 and TPS1. WT and mutant cells were grown in YPD for 3 days before staining by DHR. The mean value represents the average of two biological and two technical replicates. In each replicate, at least 10,000 cells were scored. The p values, listed below each mutant, were calculated by pairwise t-test between the WT and mutant.](https://doi.org/10.1371/journal.pgen.1006458.g007)
accumulated much higher levels of ROS than those in the rim15Δ or yak1Δ single mutants (Fig 7A), suggesting that Rim15 and Yak1 may activate the antioxidant systems in parallel to remove intracellular ROS. Removal of MCK1 from the rim15Δ or the rim15Δyak1Δ double mutants, however, did not increase the DHR-staining signals significantly, suggesting that Mck1 plays a redundant role with Rim15 or Rim15 and Yak1 to eliminate ROS (Fig 7A). To find whether the accumulation of trehalose and/or glycogen per se influences the anti-oxidant defence system, intracellular ROS levels were also determined in the gsy2Δ, tps1Δ and gsy2Δtps1Δ cells grown to early stationary phase. As shown in Fig 7B, deletion of GSY2, TPS1 or both did not greatly increase the levels of intracellular ROS. Therefore, the mild defects to resist oxidative stress in the tps1Δ cells (Fig 5B) could be attributed to their lack of protection from trehalose [35] rather than a defective antioxidant defence system. These data further confirm that the Rim15, Yak1 and Mck1 kinases may promote the extension of CLS by regulating the accumulation of storage carbohydrates as well as the anti-oxidant defence systems.

**TOR1-regulated accumulation of storage carbohydrates and CLS extension relies on Yak1, Rim15 and Mck1**

A previous study by Wei et al. [15] suggested that additional regulators other than Rim15 in the TOR signaling pathway are involved in mediating CLS extension. To find whether Yak1 and/or Mck1 are these additional regulators, we replaced TOR1 with *K. lactis* LEU2 (KILEU2) in the above WT, and the single, double and triple mutants of YAK1, RIM15 and MCK1. KILEU2 was also integrated at the lys2Δ locus to generate a wild-type strain isogenic to tor1Δ::KILEU2. Deletion of TOR1 from the WT cells was reported to enhance stress resistance and CLS [15,42]. Replacing TOR1 with KILEU2 in BY4742 mildly increased the resistance to extended heat stress (10min at 55°C in Fig 8A). The increased resistance to heat stress conferred by tor1Δ is principally dependent on Mck1 among the three kinases, and on Rim15 and Yak1 among the pair-wise combinations of the three regulators (Fig 8A). Removal of all three genes abolished the resistance to heat stress (Fig 8A), indicating that all three kinases are necessary to promote heat stress resistance enabled by tor1Δ deletion. Removal of TOR1 also marginally increased resistance to oxidative stress (Fig 8A). Enhanced resistance to oxidative stress is mostly dependent on Rim15 and Mck1 and further removal of Yak1 did not significantly reduce resistance to oxidative stress in the tor1Δ cells, similar to what was seen in the WT background (Fig 3B). Deletion of TOR1 increased the accumulation of both trehalose and glycogen (Fig 8B). Similar to what was seen in WT cells (Fig 3C), YAK1 deletion from the tor1Δ mutant increased the level of glycogen and this increase is more dependent on RIM15 than MCK1 (Fig 8B). The accumulation of trehalose in the tor1Δ cells was abolished when all three kinase genes were removed (Fig 8B), similar to what was seen in the WT background (Fig 3C).

After 3 days of growth in YPD medium, the cultures were split into two halves. One half was kept in the spent medium and the other was washed and resuspended in H2O. Deletion of TOR1 improved the CFU of the WT cells in water or in the spent medium in the first 30 days (S6A and S6B Fig). In water, which was considered as a condition of extreme calorie restriction [43–44], the ability of the tor1Δ mutant to form colonies is strongly decreased by deletion of RIM15 or MCK1, and to a lesser degree, by removal of YAK1 (Fig 8C). A further decrease of CFU, especially in the later stages of the assay (18 to 36 days), was seen when both RIM15 and YAK1 or RIM15 and MCK1 were removed (Fig 8C). In contrast, further deletion of YAK1 from the tor1Δmck1Δ mutant increased their ability to form colonies (Fig 8C), similar to what was observed when YAK1 was eliminated from the mck1Δ cells (Fig 4A) and consistent with the levels of storage carbohydrates accumulated during the transition phase (Fig 8B). Removal of all three genes dramatically reduced the ability of the tor1Δ cells to form colonies (Fig 8C),
indicating that under extreme CR conditions, TOR1-regulated quiescence exit is mediated by all three kinases.

When left in the spent medium, CFU of the tor1Δ cells is significantly decreased by deletion of RIM15 and marginally reduced by removal of YAK1 (Fig 8D). Deletion of both RIM15 and YAK1 severely reduced the ability of the tor1Δ cells to form colonies. Within 12 days, almost all the tor1Δrim15Δyak1Δ cells lost their ability to exit from quiescence (Fig 8D), similar to the defects displayed by the rim15Δyak1Δ double mutants (Fig 4A). These data confirmed that the enhanced CFU enabled by tor1Δ deletion relies on Rim15 and Yak1. In contrast, deletion of MCK1 reduced CFU of the tor1Δ cells only in the later stages of the assay (18 to 36 days, Fig 8D). This is in stark contrast to the similar CFU profiles exhibited by the rim15Δ and mck1Δ mutants in the WT background (Fig 4A). Furthermore, removal of MCK1 did not further
decrease but rather increased the CFU of the \textit{tor1}\textit{rim15}Δ or \textit{tor1}\textit{rim15}Δ\textit{yak1}Δ mutants (Fig 8D). Similarly, \textit{MCK1} deletion increased the survival rate of the \textit{tor1}\textit{rim15}Δ cells in the early/mid stationary phase (Fig 8E), contrary to the significant decrease of cell survival observed when \textit{MCK1} was removed from the \textit{rim15}Δ mutant (Fig 8F). Previously, we have shown that the parallel relationship between \textit{MCK1} and \textit{RIM15} in the accumulation of storage carbohydrates is abrogated by \textit{RAS2} deletion [21]. Put together, these data suggest that genetically compromising PKA or TOR may ameliorate the negative effects of \textit{MCK1} deletion on quiescence exit. The mechanisms underlying these observations remain to be further elucidated. Nevertheless, both Rim15 and Mck1 are necessary for long-term survival of the \textit{tor1}Δ cells in spent medium (>24 days; Fig 8E), supporting the conclusion that CLS extension enabled by \textit{TOR1} deletion is regulated by the Rim15, Yak1 and Mck1 kinases (Fig 8C).

Relative CFU at day 24 displayed by the \textit{tor1}Δ mutants in \textit{H2O} (Fig 8C) correlated well with the amount of glycogen (\(R^2 = 0.67\), S6C Fig) or trehalose (\(R^2 = 0.63\), S6D Fig) but better with the sum of glycogen and trehalose (\(R^2 = 0.78\), S6E Fig), further supporting the contention that CLS extension is dependent on the accumulation of storage carbohydrates.

\section*{Discussion}

Our analyses of a diverse range of ‘signaling’ mutants and the single, double and triple mutants of \textit{RIM15}, \textit{YAK1} and \textit{MCK1} indicate that deficiency in the accumulation of storage carbohydrates, rather than defects in the exit from the cell cycle, correlate well with the decrease of chronological lifespan (Fig 2, Fig 4 and Fig 8). Abolishing the accumulation of trehalose and glycogen dramatically reduces CLS (Fig 5). Overexpression of glycogen and trehalose biosynthetic genes, or addition of trehalose to the growth medium, rescues the defects of quiescence exit exhibited by the \textit{rim15}Δ\textit{yak1}Δ and \textit{rim15}Δ\textit{mck1}Δ mutants (Fig 6), further supporting the contention that the accumulation of trehalose and glycogen is essential to CLS extension. A positive correlation between storage carbohydrates and cell survival has been shown in chronologically aging cells [45]. Trehalose accumulation was associated with cellular proteostasis and CLS extension by calorie restriction or in \textit{tor1}Δ and \textit{sch9}Δ mutants [42,46]. Mutants unable to utilise glycogen or trehalose have significantly shortened CLS [46–47]. Put together, these and the data presented in this paper strongly support that the primary objective of the signaling pathways activated by glucose starvation is to reprogram carbon metabolism so that the transition-phase cells can accumulate sufficient energy stores to power quiescence exit (Fig 9). Trehalose seems to be a better predictor of CLS than glycogen in all but the \textit{tor1}Δ mutants tested (Figs 2, 4, 5 and 8). These data suggest that the accumulation of trehalose plays a dominant role in the extension of CLS in cells bearing normal nutrient sensing pathways. However, glycogen storage makes a significant contribution to quiescence exit and long-term survival, especially when trehalose accumulation is compromised (Figs 5 and 9).

It is likely that the accumulation of storage carbohydrates coordinated by multiple pathways requires the metabolic reprogramming induced by glucose limitation and involves the activation of mitochondrial respiration and gluconeogenesis to convert the fermentation products to energy stores (Fig 9). Firstly, in batch cultures, glycogen synthesis starts when half of the initial glucose is consumed and peaks at the beginning of the diauxic shift [48]. Similarly induced are those genes involved in glycogen biosynthesis and \textit{GAC1} [49], a positive regulator of glycogen synthase [50], which targets Glc7, the catalytic subunit of type-1 protein phosphatase, to activate Gsy2 by dephosphorylation [51–53]. Glycogen stores are partially utilised to fuel metabolic adaptations to respiratory growth and then refilled by the consumption of non-fermentative carbon sources, such as ethanol, acetate and glycerol [48,54–55]. Similarly, trehalose is accumulated during the diauxic and post-diauxic shift phases from glucose-derived
fermentation products [48]. Respiratory mutants have been shown to be defective in the accumulation of storage carbohydrates and supplementation of trehalose rescues the severe CLS defects of these mutants [14]. Secondly, the SNF1 complex is a central regulator of respiration [56–57] and the mutants of the activators of the SNF1 complex or deletion of SNF1 itself decreased the accumulation of energy stores and significantly reduced CLS (Table 1 and Fig 2). Thirdly, the Rim15/Gis1 pathway promotes the transcription of genes involved in the Krebs cycle, gluconeogenesis and the glyoxylate cycle [58–59]. The rim15Δ mutants have growth defects on non-fermentable carbon sources and they were outcompeted by WT cells in chemostat cultures limited for glucose or containing ethanol as the sole carbon source [59], indicating that the Rim15/Gis1 pathway is necessary for optimal respiratory growth (Fig 9). Furthermore, transcription of glycogen and trehalose biosynthetic genes is increased during the diauxic and post-diauxic-shift phases and this increase relies on Msn2/4 and Gis1 [60–61]. Phosphoproteomic studies have revealed that the phosphorylation status of Tsl1 and Gsy2 is regulated by Rim15 [18] and/or Mck1 [62–63]. Although the exact functions of these phosphorylations are yet to be revealed, these data suggest that these kinases may promote the accumulation of storage carbohydrates by stimulating mitochondrial respiration and gluconeogenesis to generate the substrates (UDP-Glc and Glu-6P) required for glycogen and trehalose synthesis and by modulating the relevant biosynthetic pathways at the transcriptional and post-transcriptional levels (Fig 9).

UDP-Glc is used for biosynthesis of both trehalose and glycogen. Compromising the trehalose synthesis enhanced the accumulation of glycogen (tps1Δ, Fig 5A), indicating that UDP-Glc used for trehalose synthesis is redirected towards glycogen accumulation. Glu-6P, the other substrate for trehalose synthesis, is an allosteric activator of glycogen synthase [64], suggesting that glycogen synthase activity could also be enhanced to increase glycogen accumulation when trehalose synthesis is compromised. It is intriguing to find that the Yak1 kinase

**Fig 9.** The working model showing that quiescence exit and chronological lifespan in yeast is dependent on the accumulation of storage carbohydrates and the intracellular ROS levels controlled by the kinases negatively regulated by TORC1/PKA. Yak1, Mck1 and Rim15 may also act together to negatively control the G1/S transition to limit the population entering the stationary phase. Arrow indicates activation; bar denotes inhibition and the dashed lines are regulations to be confirmed. Trehalose plays a dominant role over glycogen in CLS extension and therefore indicated by a broad arrow.

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has different roles in the accumulation of glycogen than Rim15 and Mck1 (Fig 3C). One possibility is that Yak1, Rim15 and Mck1 are all involved in the control of trehalose biosynthesis, but only Rim15 and Mck1 are implicated in glycogen accumulation (Fig 9). Given that Rim15 plays a more dominant role than Mck1 in glycogen accumulation (Fig 3C), the biosynthetic capacity directed towards glycogen in the yak1Δ mutant is more severely decreased in the rim15Δ than that in the mck1Δ cells, leading to lower levels of glycogen in the rim15Δyak1Δ than those in the yak1Δmck1Δ mutants (Fig 3C). Such a model, however, remains to be tested experimentally.

Cytotoxicity and cell death are often correlated with the levels of intracellular ROS, generated by mitochondrial respiration, ER stress, or as a result of peroxisomal dysfunction [65–66]. We have shown that the Rim15 and Yak1 act in parallel, and Mck1 has redundant function with Rim15 or Rim15 and Yak1 in their control of intracellular ROS (Fig 7A). Much higher levels of ROS were accumulated in the rim15Δyak1Δ than those in the rim15Δmck1Δ cells (Fig 7A). The rim15Δyak1Δ mutants lost their ability to exit from quiescence more quickly than the rim15Δmck1Δ cells in the WT (Fig 4A) or tor1Δ background (Fig 8D), even though the former mutants accumulated more storage carbohydrates than the latter cells (Figs 3C and 8B). These data suggest that the ability to exit quiescence may be dependent on the levels of storage carbohydrates as well as the amount of ROS accumulated in early stationary-phase cells. Trehalose supplementation restored the ability of the rim15Δmck1Δ mutants to exit from quiescence but only partially rescued the CFU defects of the rim15Δyak1Δ cells (Fig 6G and 6H). Trehalose accumulation per se did not greatly influence the levels of intracellular ROS (Fig 7B), further supporting that Rim15, Yak1 and Mck1 kinases regulate the accumulation of storage carbohydrates as well as the anti-oxidant defence systems to ensure long-term survival (Fig 9).

Previous transcript profiling indicated that starvation-induced anti-oxidant genes are upregulated by Rim15 through the activation of Gis1 and Msn2/4 [67]. In agreement with this, removal of GIS1 and MSN2/4 led to severe defects in response to oxidative stress (Fig 3B). It is likely that activation of such systems may also involve the Hsf1 transcription factor. First, we have demonstrated that expression of the pSSA3-RFP reporter is cooperatively regulated by Hsf1, Gis1 and Msn2/4 (S1 Fig). Others have shown that Hsf1 cooperates with Msn2/4 to induce the transcription of a number of starvation-induced stress genes [68–69]. Moreover, Hsf1 is confirmed as a member of the group of transcription activators that upregulate the oxidative-stress-responsive genes [70]. Starvation-induced phosphorylation and activation of Gis1 and Msn2/4 are regulated by Rim15 and Yak1 [18,26,28]. Similarly, Hsf1 phosphorylation and activation has been shown to be dependent on Snf1, Yak1 and Rim15 kinases [26,28,71]. Although it is not clear how Mck1 activates starvation-induced gene expression, these data do support the idea that the activation of the stress response and the accumulation of storage carbohydrates are co-ordinately regulated by the same set of anti-aging pathways (Fig 9).

Yak1, Rim15 and Mck1 were also shown to control the population entering the stationary phase (Fig 3D). The significant size reduction in the unbudded (Gd/G1) or budded (S-G2-M) cells (Fig 3E and 3F) and the merging of the Gd and G1 populations in the rim15Δyak1Δ or rim15Δmck1Δ FACS profiles ([21], S3 Fig) suggest that these kinases may limit population growth by negatively regulating the G1/S transition until the size threshold is reached (Fig 9). Rim15 was recently revealed as a negative regulator of the G1/S transition under nitrogen-starved or TORC1-inhibited conditions by stabilising Sic1, the inhibitor of S entry [72]. Upon nitrogen starvation, CdK Pho85 phosphorylates Hsp70 (Ssa3 is a member), triggers the displacement of the Ydj1 chaperone from Cln3 and promotes Cln3 degradation, thus delaying the onset of S phase [73]. These data suggest that starvation-activated signals may control cell size by regulating the G1/S transition directly or indirectly through the activation of the stress response. Future work should aim to reveal the molecular mechanisms by which these signals
coordinate metabolic reprogramming, stress response and the cell cycle during the transition into quiescence (Fig 9). Metabolic disorders and cell cycle dysregulations lie at the heart of many age-related diseases, such as diabetes and cancer. Revealing these mechanisms will enhance our understanding of the aging process in yeast and age-related diseases in mammals [1].

Materials and Methods

Strains and plasmids

Strains carrying single-gene deletions were obtained directly from the BY4742 mutant library (Open Biosystems). Strains carrying deletions in multiple genes were generated by combining mutations by either mating and tetrad dissection, or PCR-mediated gene replacement using drug resistant or nutritional markers [74–75]. Deletion mutants of genes coding for non-essential proteins involved in signaling pathways were selected based on data in Lee et al. [22]. Expression reporter cassettes were described previously [21]. GSY2 under the control of its endogenous promoter was cloned into pRS425 for overexpression studies. Similarly, TPS1 or TSL1 controlled by their own promoters was cloned into pRS426. Mutations of the heat shock element in the SSA3 promoter (in the pSSA3-RFP construct) were introduced by using a site-directed mutagenesis kit following the protocols described by the manufacturer (Stratagene). The second repeat of the NGAAN sequence of the HSE (5’-NGAANN2NGAANN2NGAAN-3’) was replaced by NTTAN. The new plasmid was named pSSA3(HSEΔ)-RFP (S1 Fig).

Reporter fluorescence detection and quantification

WT (BY4742) and mutant cells bearing the pSSA3-RFP constructs were grown overnight in SMM liquid medium [76] containing 2% glucose, arrayed in quadruplicates onto SMM agar plates containing 0.6% glucose using Rotor HAD (Singer Instruments) and incubated for 3 days before imaging. CellProfiler [77] was used to determine the relative levels of RFP in WT and mutants. For quantitative assays of pSSA3-RFP and pHSP12-HSP12-VFP levels in liquid cultures, freshly-grown overnight cultures were inoculated (5% v/v) into SMM medium containing 0.6% glucose which had been dispensed into 96-well microtiter plate. Cell density (OD595nm) and fluorescence intensities were simultaneously monitored in triplicate using a plate reader (BMG Biotech). RFP is excited at 580/±10nm and emits at 610/±10nm, while VFP is excited at 500/±10nm and emits at 540/±10nm. Medium-only blanks and WT cells bearing the same constructs were included for each run as negative and positive controls. After background subtraction, RFP and VFP fluorescence intensities were normalized to cell density (OD595nm). The mean and standard deviation from triplicates (Fig 1A) were calculated at each time point; for the sake of clarity, standard errors were not plotted with the means in Fig 1B.

Determination of storage carbohydrates

The concentrations of glycogen and trehalose (μg glucose per mg of wet cells) in early stationary-phase cells was determined, following the procedures described by Parrou and Francois [78] as described previously [21].

Phenotypic assays

Stress resistance conferred by cells grown to early stationary phase (after 3 days incubation in YPD (2% glucose) or buffered SC medium [41]) was determined as described previously [21]. Yeast cells were subjected to treatment at 55˚C for 5 or 10 minutes, serially diluted and spotted onto YPD agar to determine their resistance to heat shock. Similarly, cells were directly spotted
onto YPD agar plate containing 2.5mM or 5mM H₂O₂ to assay their resistance to oxidative stress.

**CLS assays**

Two different CLS measurements were adopted throughout the experiments. One was to assess the ability of stationary-phase cells to exit from quiescence to form colonies and the other to determine the viability of individual cells in the population during the stationary phase. The ability of quiescent cells to form colonies was measured every three, six or seven days by normalising colony-forming units (CFU) of stationary-phase cultures to that produced by the day 0 culture, which is early stationary phase culture after 3 days of growth in YPD (2% glucose) [21] or buffered SC medium containing 2% glucose [79]. The number of CFU is scored by spreading cells onto YPD plates after serial dilutions (1:20/1:50/1:100 for cultures grown in YPD or 1:10/1:50/1:50 for cultures grown in buffered SC medium). Cell viability was determined by FACS analysis, essentially following the protocol described by Ocampo and Barrientos [80], using 2μM of Sytox Green instead of propidium iodide. Excitation was performed using a laser at 488nm and emission detected with a standard 530/30 band pass filter.

**Analysis of cell cycle and budding index**

Cell cycle status was determined according to Haase and Reed [81] using Sytox green to stain DNA in fixed cells. Samples were sonicated at low power (2 min) and analyzed using a cytometer (LSRFortessa, Becton Dickinson). Data were processed and the percentage of budded cells (S-G₂-M) and cells carrying 3C DNA analyzed using FlowJo software (www.flowjo.com).

**FACS analysis of intracellular Reactive Oxygen Species**

Levels of intracellular ROS in live cells were determined by flow cytometry after dihydrorhodamine 123 (DHR) staining according to established procedures [82]. Briefly, 1 × 10⁷ cells were harvested by centrifugation for 1 min at 13,000rpm at room temperature; washed once with 200 μl of PBS and then resuspended in 200 μl of PBS. Aliquots of cells (50 μl) were added to 1ml PBS containing 10 μM of DHR (diluted from 10 mM stock in ethanol, Sigma-Aldrich). Following incubation in the dark at 30˚C for 60 min, the cells were harvested, washed once with 200 μl of PBS and resuspended in 1ml of PBS. After mild sonication, cells are then analyzed by flow cytometry (488nm, 530/30). Data collected from flow cytometer were processed with Flowjo software.

**Supporting Information**

S1 Fig. Starvation-induced pSSA3-RFP expression is regulated by Hsf1, Msn2/4 and Gis1. 1a: The relative levels of pSSA3-RFP in WT (BY4741) and DAmPhbfI cells; 1b: The relative levels of pSSA3-RFP and pSSA3(HSEΔ)-RFP in WT (BY4742) and msn2/4Δgis1Δ triple mutants. (PPTX)

S2 Fig. FACS profiles of WT, sbp1Δ, sak1Δ and rhr2Δ cells grown in YPD for 11h (top) and 24h (bottom). Cells encircled in red have 3C DNA. (PPTX)

S3 Fig. FACS profiles of WT, the single, double and triple deletants of rim15Δ, yak1Δ and mck1Δ during the transition into the stationary phase. At 12h, glucose is consumed in all cultures except for the yak1Δmck1Δ mutant, in which the glucose concentration is approximately 0.2%. The profiles of WT, rim15Δ, mck1Δ and rim15Δmck1Δ mutants [21] were
S4 Fig. Chronological lifespan is closely correlated with storage carbohydrates accumulated in early stationary-phase cells. 4a and 4b: Relative CFU at day 12 (4a) and day 18 (4b) is highly correlated with storage carbohydrates accumulated in WT, the single, double and triple mutants of YAK1, RIM15 and MCK1. 4c, 4d and 4e: Relative CFU at day 14 correlates poorly with glycogen, very well with trehalose, but better with total amount of carbohydrates accumulated in WT and mutants of trehalose/glycogen biosynthesis.

S5 Fig. Cell viability of WT (5a), rim15Δyak1Δ (5b) and rim15Δmck1Δ (5c) mutants bearing the empty vectors (pRS425/pRS426), GSY2/TPS1 or GSY2/TSL1 expression constructs.

S6 Fig. TOR1 deletion does not abrogate the correlation between CLS and storage carbohydrates. 6a and 6b: Deletion of TOR1 in BY4742 mildly enhances CLS in the first 30 days in H2O (6a) or in spent medium (6b). 6c, 6d and 6e: Enhanced CLS by tor1Δ deletion is mediated by YAK1, RIM15 and MCK1, and correlated well with glycogen (6c), trehalose (6d) but best with total storage carbohydrates (6e) accumulated in early stationary-phase cells.

Author Contributions
Conceptualization: NZ.
Formal analysis: NZ.
Funding acquisition: NZ SGO.
Investigation: LC YT ZQ ZZ NZ.
Methodology: NZ.
Project administration: NZ.
Resources: SGO.
Supervision: NZ.
Validation: LC NZ.
Visualization: NZ LC.
Writing – original draft: NZ LC.

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