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Arsenault HE, Roy J, Mapa CE, Cyert MS, Benanti JA. (2015). Hcm1 integrates signals from Cdk1 and calcineurin to control cell proliferation. Molecular, Cell and Cancer Biology Publications. https://doi.org/10.1091/mbc.E15-07-0469. Retrieved from https://escholarship.umassmed.edu/mccb_pubs/27

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Hcm1 integrates signals from Cdk1 and calcineurin to control cell proliferation

Heather E. Arsenault*, Jagoree Roy*, Claudine E. Mapa, Martha S. Cyert, and Jennifer A. Benanti

ABSTRACT Cyclin-dependent kinase (Cdk1) orchestrates progression through the cell cycle by coordinating the activities of cell-cycle regulators. Although phosphatases that oppose Cdk1 are likely to be necessary to establish dynamic phosphorylation, specific phosphatases that target most Cdk1 substrates have not been identified. In budding yeast, the transcription factor Hcm1 activates expression of genes that regulate chromosome segregation and is critical for maintaining genome stability. Previously we found that Hcm1 activity and degradation are stimulated by Cdk1 phosphorylation of distinct clusters of sites. Here we show that, upon exposure to environmental stress, the phosphatase calcineurin inhibits Hcm1 by specifically removing activating phosphorylations and that this regulation is important for cells to delay proliferation when they encounter stress. Our work identifies a mechanism by which proliferative signals from Cdk1 are removed in response to stress and suggests that Hcm1 functions as a rheostat that integrates stimulatory and inhibitory signals to control cell proliferation.

INTRODUCTION

Cyclin-dependent kinases (Cdks) orchestrate progression through the cell division cycle by phosphorylating hundreds of regulatory proteins in a defined order (Ubersax et al., 2003; Holt et al., 2009). Disruption of this ordered phosphorylation can result in errors in DNA replication and chromosome segregation that can be lethal or result in genomic instability that can lead to cancer (Hanahan and Weinberg, 2011). The activities of Cdks are opposed by phosphatases, which are equally important for establishing the cyclical phosphorylation patterns that drive the cell cycle. However, whereas a great deal is known about how Cdks recognize and target substrates, much less is known about the phosphatases that antagonize Cdk function (Mochida and Hunt, 2012). The best-understood phosphatases that function in cell cycle control are those that counteract Cdk1 to regulate mitosis. These include Cdc14, PP1, and PP2A (Visintin et al., 1998; Domingo-Sananes et al., 2011; Wurzenberger and Gerlich, 2011; Grallert et al., 2015). In addition, a few phosphatases, including PP2A (Mochida and Hunt, 2007; Alvarez-Fernández et al., 2011), PP4 (Toyo-oka et al., 2008), and Caenorhabditis elegans CDC-14 (Saito et al., 2004), have been found to remove Cdk-catalyzed phosphorylations in interphase. However, for the majority of Cdk substrates, their cognate phosphatases remain to be identified, and the extent to which phosphatases play direct roles in controlling progression through interphase is not known.

The calcium-activated phosphatase PP2B/calcineurin (CN) has also been implicated in cell cycle control. CN is required for progression through meiosis in Xenopus and Drosophila (Cao et al., 2006; Mochida and Hunt, 2007; Nishiyama et al., 2007; Takeo et al., 2010). In Xenopus oocytes, CN directly removes Cdk1-catalyzed phosphorylations from substrates to trigger cell cycle reentry (Cao et al., 2006; Mochida and Hunt, 2007). The role of CN in controlling the mitotic cell cycle is less clear. Positive genetic interactions between Cdk1 (cdc28) and CN (cnb1) mutants in budding yeast suggest that CN may antagonize Cdk1 phosphorylation, and CN targets include known Cdk1 substrates (Fiedler et al., 2009;
Goldman et al., 2014). Moreover, CN activation delays the cell cycle in yeast strains lacking Zds1 and Zds2 (Miyakawa and Mizunuma, 2007), which are regulatory subunits of the phosphatase PP2A (Rossio and Yoshida, 2011), suggesting that CN and PP2A may act redundantly to arrest the cell cycle in some contexts. In addition, our recent work identified a number of CN targets involved in polarized growth, which is coordinated with the cell cycle (Goldman et al., 2014). Thus, although a role for yeast CN in mitotic cell cycle regulation seems likely, this function has yet to be elucidated.

Among the key targets of Cdk1s in all eukaryotes are cell cycle-regulatory transcription factors, which coordinate gene expression with the cell cycle (Bertoli et al., 2013; Sadasivam and DeCaprio, 2013). In budding yeast, Cdk1 phosphorylation regulates the activity of the forhead family transcription factor Hcm1, which is a homologue of the human oncogene FoxM1 (Myatt and Lam, 2007). Like FoxM1, Hcm1 activates expression of genes that are required for accurate chromosome segregation, including molecular motors, components of the spindle pole body, and the kinetochores (Laoukili et al., 2005; Pramila et al., 2006; Grant et al., 2013). Consistent with the functions of these target genes, mutations that inactivate Hcm1 sensitize cells to microtubule poisons that destabilize the mitotic spindle (Horak et al., 2002; Daniel et al., 2006), cause an increased rate of chromosome loss (Pramila et al., 2006), and are lethal when combined with mutations in spindle checkpoint genes for robust proliferation.

Regulation of Hcm1 by calcineurin
Hcm1 activates expression of genes that regulate chromosome segregation and mitosis (Pramila et al., 2006). As a result, deletion or inactivation of HCM1 affects progression through the cell cycle. This cell cycle defect is easily observed when mutant cells are cocultured with wild-type cells in a competitive fitness assay, which is a sensitive growth assay that reveals differences in proliferation rate. Previously we found that blocking all phosphorylation of Hcm1 by Cdk1 led to a reduction in cellular fitness (hcm1-15A; Figure 1B; Landry et al., 2014), thus demonstrating that regulation of Hcm1 by Cdk1 is critical for robust proliferation.

Here we wanted to address whether phosphoregulation limits Hcm1 activity during the cell cycle. To answer this question, we examined the fitness of cells expressing Hcm1 phosphosite mutants that have increased activity. Strains expressing a mutant that is highly expressed because it has mutations that mimic phosphorylation at activating sites (hcm1-16E) and a mutant that is constitutively active destabilizing phosphosites, CN inactivates Hcm1 without disrupting ubiquitin-mediated degradation. This decrease in Hcm1 activity contributes to decreased proliferation in response to stress, since blocking Hcm1 dephosphorylation allows cells to proliferate better in response to CN-activating stresses. In addition, cells expressing a CN-resistant mutant of Hcm1 are fitter than wild type cells in the absence of stress, demonstrating that CN directly antagonizes Cdk1 activity to control proliferation.

RESULTS AND DISCUSSION
Phosphorylation of Hcm1 regulates proliferation
Hcm1 activates expression of genes that are required for robust proliferation.
Calcineurin inactivates Hcm1

To determine the consequences of Hcm1 dephosphorylation, we first examined whether CN regulates Hcm1 expression. If CN does not target N-terminal Cdk1 sites that promote phosphorylation-mediated degradation of Hcm1, as our data suggest (Figure 3, A and B), then CN activation should not stabilize Hcm1. Consistent with these observations, CN was found to target several Cdk1 substrates in a recent proteomic screen (Goldman et al., 2014), it is not known whether it directly regulates proliferation. To determine whether CN regulates proliferation via dephosphorylation of Hcm1, we examined Hcm1 phosphorylation in vivo after CN activation. We first established a Western blotting assay using Phos-tag reagent, which enables the resolution of individual phosphosites upon its addition to a polyacrylamide gel (Kinoshita et al., 2006). Under these gel conditions, the phosphorylation status of a panel of Hcm1 mutants with different numbers of Cdk1 phosphosites is clearly distinguishable (Figure 2, A and C). In addition, we found that within 10 min of direct CN activation by the addition of CaCl₂ to the growth medium, Hcm1 was dramatically dephosphorylated (Figure 2D). This dephosphorylation was blocked by deletion of the CN docking site in Hcm1 (ΔP; Figure 2D), by deletion of the regulatory subunit of CN, Cnb1 (Figure 2D), or upon addition of the CN inhibitor FK506 (Figure 2E). These data demonstrate that Hcm1 is dephosphorylated by CN in vivo.

Of note, Hcm1 retained some phosphorylation after CN activation (Figure 2, D and E), suggesting that CN might target only a subset of Hcm1 phosphosites. To test this, we examined CN-dependent dephosphorylation of previously characterized mutants in which all Cdk1 sites were mutated except for the eight activating Cdk1 sites (Hcm1-7N, with 7 N-terminal S/T-P sites mutated to A-P; Figure 2A) or the three destabilizing Cdk1 sites (Hcm1-12C, with 12 C-terminal S/T-P sites mutated to A-P; Figure 2A; Landry et al., 2014). Of interest, Hcm1-7N was almost completely dephosphorylated after CN activation, whereas Hcm1-12C phosphorylation was largely unchanged (Figure 3A). This specificity was also observed in vitro. Recombinant Hcm1 proteins were phosphorylated with Clb2/Cdk1 and then incubated with or without purified CN. Consistent with the in vivo results, CN dephosphorylated wild-type Hcm1 and Hcm1-7N but had no effect on Hcm1-12C (Figure 3B and Supplemental Figure S1B). In addition, deletion of the PSIEIQ motif impaired Hcm1 dephosphorylation in vitro (Figure 3B and Supplemental Figure S1B), although it was not completely blocked. This partial dephosphorylation of the APSIEIQ mutant suggests that this motif is less important to mediate the interaction between CN and Hcm1 in vitro than in vivo, where there are hundreds of other CN targets present that reduce the concentration of available CN. These results show that Hcm1 can be directly dephosphorylated by CN and demonstrate that CN has specificity for C-terminal Cdk1 sites that are required for Hcm1 activity.

Calcineurin inactivates Hcm1

Hcm1 is a target of the phosphatase calcineurin

In a previous yeast two-hybrid screen, we identified Hcm1 as a candidate substrate of the conserved Ca²⁺-activated phosphatase CN (unpublished data). Hcm1 interacted with the CN-regulatory subunit Cna1 in this assay, and the interaction was eliminated upon deletion of a six–amino acid sequence on Hcm1 (PSIEIQ; Figure 2, A and B) that matches the consensus for the previously identified CN docking-site sequence (Roy et al., 2007). In addition, we found that Hcm1 associated with Cna2 in vivo, and this interaction was inhibited by deletion of the docking site (Supplemental Figure S1A). These data suggest that CN might antagonize Hcm1 phosphorylation by Cdk1 to regulate its activity and affect proliferation.

The best-understood role of CN in yeast is to promote cell survival in response to environmental stresses that signal through an increase in intracellular Ca²⁺ (Cyert and Philpott, 2013). Although
with this prediction, CaCl₂ treatment did not lengthen Hcm1 half-life (Figure 3, C and D). In fact, Hcm1 half-life was modestly decreased after CaCl₂ treatment. Of importance, deletion of the CN docking site or expression of wild-type Hcm1 in a CN-deficient strain also did not lengthen Hcm1 half-life (Figure 3, C and D), and deletion of the CN docking site did not affect cell cycle–regulated expression of Hcm1 (Supplemental Figure S2A). Together these data support the finding that the N-terminal phosphosites in Hcm1 are not targeted by CN. They also suggest that there may be an active mechanism to further destabilize Hcm1 when cells are exposed to stress. This destabilization appears to be independent of CN and Cdk1, since the half-life of all mutants were shortened. One possibility is that the previously identified Cdk1-independent mode of Hcm1 degradation that occurs in G1 phase (Landry et al., 2014) may be enhanced by CN. Moreover, target gene expression was largely unchanged in cells expressing the Hcm1 docking-site mutant (hcm1ΔPSIEIQ) or Hcm1-16E, which contains phosphomimetic mutations in activating Cdk1 sites and restores Hcm1 binding to each of these promoters (red and green bars, Figure 4C; Landry et al., 2014). Of importance, wild-type and mutant cells displayed similar cell cycle distributions after CaCl₂ treatment (Supplemental Figure S2B), ruling out this potential indirect effect on expression of Hcm1 target genes. Moreover, hcm1ΔPSIEIQ cells did not exhibit sensitivity to the microtubule poison benomyl (Supplemental Figure S2C), confirming that Hcm1ΔPSIEIQ is a functional protein. These findings demonstrate that CN impairs Hcm1 activation and are consistent with our other data suggesting that activating sites on Hcm1 are selectively dephosphorylated by CN.

**Dephosphorylation of Hcm1 by calcineurin impairs proliferation**

Although no role for CN in control of an unperturbed cell cycle has been described, the fact that the hcm1-1⁰E phosphomimetic mutant outcompetes a wild-type strain in coculture assays suggests that Hcm1 is not fully phosphorylated when cells are grown in rich medium without any additional stresses (Figure 1B) and that a phosphatase may actively remove phosphorylations at these sites. To determine whether CN plays a role in this regulation, we tested whether the Hcm1ΔPSIEIQ mutant, which severely impairs dephosphorylation of these same sites (Figure 3 and Supplemental Figure S1B), displays a similar increase in fitness. Indeed, hcm1ΔPSIEIQ cells consistently exhibited a modest proliferative advantage in this assay (Figure 5A), suggesting that there may be a low level of CN activity in normal growth conditions and that CN contributes to the phosphorylation status of Hcm1.

CN is strongly activated in response to several types of environmental stress, including alkaline pH (Viladevall et al., 2004), toxic cations (Nakamura et al., 1993; Matsumoto et al., 2002), and cell wall
FIGURE 4: Calcineurin inactivates Hcm1. (A) Changes in expression of predicted Hcm1 target genes (Pramila et al., 2006) in response to CaCl2 treatment with or without the CN inhibitor FK506. Data are from Yoshimoto et al., (2002). Cluster 1 includes 49 of 91 genes that are down-regulated (less than $-0.5 \log 2$-fold change) at the 30-min time point. Cluster 2 includes the remaining 42 genes. (B) Average expression of genes in each cluster over time with or without FK506. For cluster 1, average values with or without FK506 are significantly different at each time point ($p < 0.0001$, paired t-test); for cluster 2, average values with or without FK506 are not significantly different at any time point. (C) Reverse transcription quantitative PCR of Hcm1 target genes 30 min after the addition of CaCl2. Fold change values were calculated by comparing expression after 30 min to expression in the same strain before treatment. Average log 2-fold change values ±1 SD ($n = 6$). Down-regulation was significantly impaired in each mutant strain compared with wild type. ****$p < 0.0001$, ***$p < 0.001$, **$p < 0.01$, *$p < 0.05$.

stress (Levin, 2011), so we next examined the importance of Hcm1 dephosphorylation for the cellular response to these stresses. Of interest, cells expressing Hcm1 mutants with varying amounts of activity responded differently to different classes of CN-activating stresses. The presence or absence of Hcm1 activity had no effect on survival when cells were exposed to alkaline stress (Supplemental Figure S3). However, Hcm1 activity was important for the response to cell wall stress and LiCl, both of which promote Hcm1 dephosphorylation (Figure SB). Deletion of HCM1 sensitized cells to both types of stress (Figure S5, C and D, and Supplemental Figure S3), and when Hcm1 dephosphorylation was impaired (by deletion of the docking site or expression of the phosphomimetic mutant), proliferation was enhanced (Figure S5, C and D). We also examined the hcm1-3N strain, which, unlike hcm1-16E and hcm1APSEIQ, is highly resistant to benomyl (Supplemental Figure S2C). Of note, hcm1-3N cells showed similar resistance to CN-activating stresses as cells expressing Hcm1APSEIQ, Hcm1-16E, or mutants that combined either the APSEIQ mutation or the 16E mutation with the 3N mutation (Figure S, C and D). Thus Hcm1 activity limits proliferation during some stress conditions, and increasing either its level or activity through modulation of its phosphorylation state results in increased proliferation.

The wide array of CN targets that have been identified thus far suggests that CN orchestrates a global, integrated response to stress by affecting numerous regulatory pathways in order to promote cell survival in response to environmental stress (Heath et al., 2004; Bultynck et al., 2006; O’Donnell et al., 2013; Alvaro et al., 2014; Goldman et al., 2014; Guiney et al., 2015). In this study, we identify Hcm1 as an additional target and elucidate how CN connects this global stress response with changes in the cell cycle–regulatory network. In addition, we demonstrate that Hcm1 is a key node in the cell cycle network that relays signals from the extracellular environment to control proliferation. This is supported by our finding that increases or decreases in Hcm1 phosphorylation can positively or negatively affect fitness (Figure 1) and that in response to stress, CN targets a subset of Hcm1 phosphosites. Of importance, there are two groups of Cdk1 phosphorylation sites that have opposing effects on Hcm1 activity, and CN specifically targets the group of sites that promote Hcm1 function (Figure 3). By dephosphorylating activating sites while sites that promote degradative remain intact, CN rapidly extinguishes Hcm1 activity. Similarly, an additional phosphatase may regulate Hcm1 stability by dephosphorylating the N-terminal Cdk1 sites, thereby increasing Hcm1 levels. Thus Hcm1 activity is differentially modulated by multiple regulators, which likely respond to distinct signals. Because its activity is limiting for maximal proliferation, we propose that Hcm1 serves as a biological rheostat that integrates multiple signals from kinases and phosphatases to produce a broad continuum of proliferation rates. Further, this mode of cell cycle regulation might be conserved, as several transcription factors that control late–cell cycle gene expression in human cells are similarly regulated by Cdk phosphorylation (Sadasivam and DeCaprio, 2013). Understanding the role of phosphatases in transmitting signals to the cell cycle–regulatory network is key to elucidating how cell cycle progression is finely tuned to match the cellular environment.

MATERIALS AND METHODS

Yeast strains and growth conditions

A complete list of strains used in each experiment is given in Supplemental Table S1. All strains are in the S288c background
except for PJ69-4A (which is W303). For all HCM1 mutations, PCR products containing the desired mutations were integrated with a triple hemagglutinin epitope tag (3HA) and the HIS3MX cassette at the genomic locus using standard techniques. Each HCM1 mutation was confirmed by sequencing. The HCM1 cnb1Δ strain was generated by replacing the CNB1 gene with a KanMX cassette in the Hcm1-3HA-tagged strain. Cells were grown in either rich medium (YM-1 complete medium with 2% dextrose; Benanti et al., 2007) or synthetic medium (C medium with 1% ammonium chloride, 2% dextrose) at 30°C. For Ca²⁺ treatments, cells were grown overnight in rich medium and then transferred into synthetic medium and allowed to grow for at least one cell cycle. Cells were then treated with 200 mM CaCl₂ for the indicated times. Where indicated, cells were pretreated with 1 μg/ml FK506 (LC Laboratories, Woburn, MA) in ET buffer (90% ethanol and 10% Tween-20) or ET buffer alone for 1 h before CaCl₂ treatment. Where indicated, exponentially growing cells in rich medium were treated with 500 mM LiCl for 5 min or 250 μg/ml Congo red for 10 min. For cell cycle analysis, cells were arrested in G1 phase in rich medium containing 10 μg/ml α-factor for 2 h and then released into medium without α-factor. Flow cytometry to confirm cell cycle position was carried out as previously described (Landry et al., 2014).

Yeast two-hybrid assay
Strain PJ69-4A was transformed with GAL4-DBD and GAL4-ACT fusion plasmids: BJP2014 (CNA1-GAL4 activation domain fusion, LEU2), pACT2 (GAL4 DNA-binding domain [DBD], TRP1), pACT2-HCM1 (HCM1-GAL4 DBD fusion, TRP1), and pACT2-hcm1ΔPSIEIQ (hcm1ΔPSIEIQ-GAL4 DBD fusion, TRP1). Cotransformants were scored for growth on synthetic medium with or without histidine by dilution plating: from 0.5 to 1 OD₆₀₀ unit of cells from each culture were serially diluted fivefold to sixfold in distilled water and spotted on plates. Plates were incubated at 30°C for 2–3 d.

In vivo CN interaction assay
Strain YEG2 (Guiney et al., 2015) was transformed with plasmids pGAL-HCM1 (Landry et al., 2014), pGAL-hcm1-3N (Landry et al., 2014), and pGAL-hcm1ΔPSIEIQ (same as pGAL-HCM1 with hcm1ΔPSIEIQ) or vector (GAL-YEP352). Transformants were grown to mid log phase in synthetic media lacking histidine and containing 2% raffinose. Expression of the GAL1 promoter was induced with 2% galactose for 4 h, and 200 mM CaCl₂ was added to the cultures for 15 min to activate CN. Cells were then pelleted, washed, and frozen at −80°C. Cell lysates were prepared as described (Goldman et al., 2014), and 10 mg of cell lysates was incubated with 30 μl of immunoglobulin G-Sepharose (GE Healthcare, Pittsburgh, PA) for 1 h at 4°C. ZZ-tagged complexes were then precipitated and washed twice with buffer. Bound proteins were eluted by boiling in 2× SDS-dye and examined by SDS–PAGE and Western analysis with a Li-COR detection system. Monoclonal anti-HA antibody (12CA5) was used to detect HA-tagged proteins, and a polyclonal anti-S-tag antibody (kind gift from R. Kopito, Stanford University) was used to detect Cna2-S-ZZ.

Competition assays
Competition assays were performed as previously described (Torres et al., 2010; Landry et al., 2014). An equal amount of cells with or without PGK1-GFP was mixed together and diluted every 12 h to maintain logarithmic-phase growth. Cells were fixed at each time point in 100% ethanol for analysis by flow cytometry using a FACScan (Becton Dickson, Franklin Lakes, NJ). Data were analyzed for GFP fluorescence using FlowJo (FLOWJO, LLC, Ashland, OR) software.

Western blotting
Cell pellets (1 OD₆₀₀ nm) were lysed in trichloroacetic acid (TCA), and Western blotting was carried out as previously described (Landry et al., 2014), with antibodies against HA (12CAS), Cdc28 (sc-6709; Santa Cruz Biotechnology, Santa Cruz, CA). For Phos-tag gels, the...
In vitro dephosphorylation assays
Hcm1 and indicated mutants were cloned into the pET32mLic vector (hexahistidine-tagging vector), expressed in bacteria, and purified on Ni nitriloacetic acid agarose beads (Qiagen, Hilden, Germany) according to manufacturer’s specifications. Proteins were eluted and stored in buffer containing 50 mM Tris-HCl, pH 7.5, 150 mM NaCl, 1 mM β-mercaptoethanol, and 10% glycerol. From 20 to 30 μg of purified protein was phosphorylated by Cib2/Cdk1/Cks1 complex) a kind gift from M. Kőváromágyi and J. Skotheim (Stanford University) in kinase buffer (50 mM 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid, pH 7.4, 150 mM NaCl, 5 mM MgCl₂, 500 mM ATP) containing [γ-32P]ATP as in Kőváromágyi et al. (2011) for 16 h at room temperature. Dephosphorylated proteins were purified from unincorporated ATP using a Centri-sep (Applied Biosystems, Germany) according to manufacturer’s specifications. Proteins were supported by National Institutes of Health Grant R01GM048729.

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