Phosphorylation by Cdc28 Activates the Cdc20-dependent Activity of the Anaphase-promoting Complex

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Abstract. Budding yeast initiates anaphase by activating the Cdc20-dependent anaphase-promoting complex (APC). The mitotic activity of Cdc28 (Cdk1) is required to activate this form of the APC, and mutants that are impaired in mitotic Cdc28 function have difficulty leaving mitosis. This defect can be explained by a defect in a PC phosphorylation, which depends on mitotic Cdc28 activity in vivo and can be catalyzed by purified Cdc28 in vitro. Mutating putative Cdc28 phosphorylation sites in three components of the APC, Cdc16, Cdc23, and Cdc27, makes the APC resistant to phosphorylation both in vivo and in vitro. The nonphosphorylatable APC has normal activity in G1, but its mitotic, Cdc20-dependent activity is compromised. These results show that Cdc28 activates the APC in budding yeast to trigger anaphase. Previous reports have shown that the budding yeast Cdc5 homologue, Plk, can also phosphorylate and activate the APC in vitro. We show that, like cdc28 mutants, cdc5 mutants affect APC phosphorylation in vivo. However, although Cdc5 can phosphorylate Cdc16 and Cdc27 in vitro, this in vitro phosphorylation does not occur on in vivo sites of phosphorylation.

Key words: mitosis • budding yeast • Cdc5 • Cks1 • Pds1

Introduction

Proteolysis plays a critical role in the eukaryotic cell cycle. During the exit from mitosis, ubiquitin-mediated proteolysis destroys an inhibitor of sister chromatid separation (Pds1 in budding yeast and Cut2 in fission yeast; Holloway et al., 1993; Funabiki et al., 1996; Yamamoto et al., 1996) and the mitotic cyclins (Clb1–Clb4 in budding yeast; Hirata et al., 1991; Lotzer et al., 1991; Yaman et al., 1996). These proteins are targeted for degradation by the anaphase-promoting complex (APC)1 or cyclosome, which is the E3 ubiquitin ligase for cyclins (King et al., 1995; Sudakin et al., 1995; Zechariae et al., 1996), Pds1 (Cohen-Fix et al., 1996; Funabiki et al., 1997), and other substrates (Juang et al., 1997; Prinz et al., 1998; Shirayama et al., 1998), marking them for destruction by the 26S proteosome. The APC is regulated by the binding of two conserved activators, Cdc20 and Hct1 (also known as Cdh1; Schlab et al., 1997; Visintin et al., 1997; Fang et al., 1998b; Kitamura et al., 1998; Lorca et al., 1998). In budding yeast, Cdc20-dependent APC activity initiates the metaphase to anaphase transition and the series of events that activate the Hct1-dependent APC, which induces complete mitotic cyclin destruction (Lim and Surana, 1995; Visintin et al., 1995; Shirayama et al., 1999). Hct1 acts in conjunction with the cyclin-dependent kinase (Cdk) inhibitor Sic1 to induce the rapid drop in Cdc28-associated kinase activity that drives cells out of mitosis and into the next G1 (Mendenhall, 1993; Donovon et al., 1994; Amon, 1997; Li and Cai, 1997). The Hct1- and the Cdc20-dependent APC can both target Pds1 for destruction (Visintin et al., 1997; Rudner et al., 2000), suggesting that the main difference between them is the time during the cell cycle when each is active (Prinz et al., 1998).

Phosphorylation of Hct1 by Cdc28/C1b complexes keeps it from binding or activating the APC (Zechariae et al., 1998; Jaspersen et al., 1999). This phosphorylation is removed by Cdc14, a phosphatase that is activated after Cdc20-dependent destruction of Pds1, C1b2, and the S-phase cyclin, C1b5 (Visintin et al., 1998; Jaspersen et al., 1999; Shirayama et al., 1999; Yoon et al., 2000). The late activation of Cdc14 ensures that cells do not inactivate Cdc28 and exit mitosis until well after they have initiated sister chromatid segregation.

Cdc20 is regulated in at least three ways: the gene is transcribed only in mitosis, the protein is targeted for destruction by the APC, and Cdc20 activity is inhibited by the spindle checkpoint, which monitors whether chromo-
some strains have attached to the spindle properly (Weinstein, 1997; Fang et al., 1998a; Hwang et al., 1998; Kallio et al., 1998; K im et al., 1998; K ramer et al., 1998; Prinz et al., 1998; Shirayama et al., 1998).

The Cdc20-dependent A PC is regulated by phosphorylation. A PC subunits are phosphorylated in fission yeast, frogs, clams, and mammalian tissue culture cells (Hershko et al., 1994; Peters et al., 1996; Y amada et al., 1997; K otani et al., 1998). Phosphorylation correlates with A PC activity in vivo, and experiments in vitro have suggested that phospho-rylating the A PC regulates Cdc20 binding and A PC activity (K otani et al., 1998, 1999; Shteenberg et al., 1999).

Studies in frog egg extracts and mammalian tissue culture cells have shown that the protein kinase Plk (known as Cdc5 in budding yeast and Plx1 in frogs) and the complex of Cdc2, Cyclin B, and Cks1, a small Cdk binding protein, can phosphorylate the A PC in vitro. Depletion of either Cks1 or Plx1 from frog extracts blocks cyclin destruction, suggesting that both Cdc2 and Plx1 may activate the A PC (Patra and Dunphy, 1996; D escombes and N igg, 1998; K otani et al., 1998, 1999), but the relative importance of these two kinases in vivo is unclear. Phosphorylation of the A PC by a MAP-dependent protein kinase A inhibits the A PC both in vivo and in vitro (Y amashita et al., 1996; K otani et al., 1998). Lastly, protein phosphatase 2A (PP2A) inhibits the A PC (Lahav-Baratz et al., 1995; Shteenberg et al., 1999), whereas PP1 activates the A PC (Y amada et al., 1997).

In the accompanying paper (Rudner et al., 2000), we show that CDC28-T18V, Y19F (CDC28-VF), and other mutants with altered mitotic Cdc28 activity are compromised in activating the Cdc20-dependent A PC, revealing a requirement for Cdc20 in A PC activation. Here, we show that CDC28-VF is defective in the mitotic phosphorylation of the A PC and that this phosphorylation depends on Cdc20 activity both in vivo and in vitro. Mutating potential phosphorylation sites in the A PC components Cdc16, Cdc23, and Cdc27 reduces Cdc20 binding to the A PC and Cdc20-dependent A PC activity in vivo.

Materials and Methods

Strain and Plasmid Construction

Table I lists the strains used in this work. A ll strains are derivatives of the W303 strain background (W303-1a; Rodney Rothstein, Columbia University, New York, NY ). Standard genetic techniques were used to manipulate yeast strains (Sherman et al., 1974) and standard protocols were used for DNA manipulation (Maniatis et al., 1982). A ll deletions and replacements were made with pAFS120 (Hwang and Murray, 1997). Details on the use of these antibodies can be found in the accompanying paper (Rudner et al., 2000).

To resolve the phosphorylated forms of Cdc27 by Western blot, samples were electrophoresed on a 12.5% polyacrylamide gel containing 0.025% bisacrylamide. The phosphorylated forms of Cdc27 were resolved by periodic acid on a 10% polyacrylamide gel containing 0.13% bisacrylamide.

The following antibodies were used in this study: 9E10 ascites (B AbC O); affinity-purified rabbit polyclonal anti-C1d2 and anti-C1d3 antibodies (K ellogg and Murray, 1995); rabbit polyclonal anti-Sic1 serum (a gift of M ike M endenhall, University of Kentucky, Lexington, KY); 12CA5 ascites (B AbC O); rabbit polyclonal anti-Cdc16, anti-Cdc23, and anti-Clb2 (Lamb et al., 1994); and rabbit polyclonal anti-Cdc26 antibody (M. w. and M. u. r., 1995). Details on the use of these antibodies can be found in the accompanying paper (Rudner et al., 2000).

In Vivo Labeling of the APC

Yeast cells were arrested in G1 with alpha factor, in S-phase with HU, and in mitosis by spindle checkpoint activation and temperature shift. Once the cells were arrested at the indicated stage of the cell cycle, 50 ml of OD600 0.8 cells were harvested by centrifugation, washed twice in H2O, and resuspended in 1 ml phosphate-free complete synthetic medium (Roth- blatt and Schekman, 1989) containing 0.5-1.5 mCi 32P-O4 (A merham Phar- macia Biotech). Cells were labeled for 1 h, harvested by centrifugation, washed once in H2O, and then were frozen in screw-cap tubes (Sarstedt). These tubes were used throughout the procedure to prevent radioactive contamination. The frozen yeast pellets were processed for immunopre- cipitation as described in the accompanying paper (Rudner et al., 2000).

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with the following modifications. 2–3 μg anti-Cdc26 antibody was bound to 20 μl protein A beads for 20 min on ice. These beads were then incubated with 10–20 μg of unlabelled C-lysatemade from cdc26a cells for 1–2 h. A fter incubation, the beads were washed twice in lysis buffer. A t the same time, the labeled cell lysate (typically 10 mg) was preclari ed in 75 μl protein A CL-4B Sepharose beads (Sigma-Aldrich) for 1 h, and then centrifuged at 14,000 rpm for 5 min at 4°C. The labeled lysate was then added to the antibody-bound protein A beads and incubated with rotation for 1–2 h. The beads were washed four times with kinase bead buffer (500 mM NaCl, 50 mM Tris-Cl, pH 7.4, 50 mM NaF, 5 mM EDTA, 0.3% Triton X-100; transferring the beads to fresh tubes after the fourth wash), and then twice with 50 mM Tris-Cl, pH 7.5. The beads were then rotated in 50 mM Tris-Cl, pH 7.5, containing 0.5 mg/ml RNAse A for 30 min at 4°C, washed an additional two times in kinase bead buffer (transferring the beads to fresh tubes after the second wash), and then a final wash in 50 mM Tris-Cl, pH 7.5.

In Vitro Phosphorylation of the APC

Cells were arrested in G1 by alpha factor, were harvested by centrifugation, frozen, and processed for immunoprecipitation. 10–15 mg of cell lysate was preclari ed in 50 μl protein A beads, and then the APC was immunoprecipitated with 2 μg anti-Cdc28 antibodies that were prebound to protein A beads as described above. After immunoprecipitation, the beads were washed three times in kinase bead buffer (transferring the beads to fresh tubes after the second wash), and then twice in low salt kinase buffer (10 mM NaCl, 20 mM Hepes-KOH, pH 7.4, 5 mM MgCl2, 1 mM DTT), 5 μg of purified Cdc28-His6, 50 ng purified Cdc2-MBP (gifts of Jeff Ubersax, University of California, San Francisco, CA), and 100 ng purified Cks1 (see below) in 2 μl of kinase dilution buffer (300 mM NaCl, 25 mM Hepes-KOH, pH 7.4, 10% glycerol, 0.1 mg/ml BSA) were added to a 13 μl of low salt kinase buffer containing 10 μM ATP, 2 μM okadaic acid (Calbiochem-Novabiochem). This reaction mix was added to the immunoprecipitated APC and incubated at 25°C for 20 min. The beads were then washed three times in kinase bead buffer containing 1 μM okadaic acid (transferring the beads to fresh tubes after the second wash), and then twice in low salt kinase buffer containing 1 μM okadaic acid. These washes remove Cib2-MBP and proteolytic fragments of Cib2-MBP, which are well phosphorylated and obscure A PC phosphorylation. Cdc5 phosphorylation was performed by adding the following to immunoprecipitated A PC: purified His6-HA-Cdc5 (a gift of Julia Charles, University of California, San Francisco, CA) in 5 μl of Cdc5 storage buffer (250 mM KCl, 20 mM Hepes-KOH, pH 7.4, 10% glycerol, 5 mM NaF, 0.1 mg/ml BSA) added to 15 μl of Cdc5 kinase reaction buffer (20 mM KCl, 20 mM Hepes-KOH, pH 7.4, 2 mM MgCl2, 2 mM MnCl2, final concentrations in

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**Table I. Strain List**

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*All strains are isogenic to W303-1a (MATa ade2-1 can1-100 his3-11,15 leu2-3,112 trp1-1 ura3-1). All MATa strains are derived from crosses with KH153.

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Rudner and Murray Cdc28 Phosphorylates the APC

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factor-arrested cells (Hardy and Pautz, 1996; Charles et al., 1997) using lambda phosphatase (New England Biolabs, Inc.).

Cdc5, the Plk homologue in budding yeast, was required to activate the Cdc20-dependent APC, suggesting that the budding yeast APC is activated by Cdc20. Therefore, we tested whether Cdc5 phosphorylates the APC isolated from cells containing Cdc20, a nonessential component of the APC (Hwang and Murray, 1997), and used these immunoprecipitates as a substrate for purified recombinant Cdc28/Clb2/Cks1 (a gift of Jeff Ubersax and David Morgan, University of California, San Francisco, CA) in the presence of [γ-32P]ATP. The Western blot shows that similar amounts of APC were precipitated in the presence of anti-Cdc26 antibody, but no phosphorylation was observed in the absence of added Cdc28/Clb2/Cks1. However, a kinase bound to the APC; no labeling is seen in immunoprecipitates lacking added Cdc28, Clb2, or Cks1 was added to kinase reaction (no kinase).

Cdk28 Phosphorylates the APC In Vitro

Mutants that reduce mitotic Cdk28 activity have difficulty activating the Cdc20-dependent APC, suggesting that Cdk28 might phosphorylate the APC or Cdc20 (Rudner et al., 2000). Therefore, we asked if the budding yeast APC is phosphorylated in vitro. We used an A PC that was isolated by immunoprecipitation of cell lysates with antibodies against Cdc26, a nonessential component of the APC (Hwang and Murray, 1997), and used these immunoprecipitates as a substrate for purified recombinant Cdc28/Clb2/Cks1 (a gift of Jeff Ubersax and David Morgan, University of California, San Francisco, CA) in the presence of [γ-32P]ATP. In APC isolated from wild-type cells, three major bands and a single minor band were phosphorylated (Fig. 1, top). We determined the identity of these four bands by phosphorylating the APC isolated from cells containing epitope-tagged subunits that change their molecular weight. If the band shifted up in the epitope-tagged A PC, we concluded that the phosphorylated protein is the A PC subunit. By this criterion, the protein at 97 kD is Cdc16, the protein at 85 kD is Cdc27, and the minor species at 65 kD is Cdc23 (Fig. 1, top). Similar experiments have shown the band at 42 kD is A pc9 (data not shown).

We do not think the phosphorylation of the A PC in these reactions is due to kinases that coimmunoprecipitate with the A PC; no labeling is seen in immunoprecipitates lacking added Cdc28/Clb2/Cks1. However, a kinase bound to the A PC might need to be activated by Cdc28, as has been reported for Plk phosphorylation of the mammalian APC (Kotani et al., 1998). Therefore, we tested whether Cdc5, the Plk homologue in budding yeast, was required for in vitro APC phosphorylation (Kitada et al., 1993). We isolated the A PC from a cdc5-1 mutant that had been arrested in G1 by alpha factor at 25°C and then shifted to the restrictive temperature of 37°C for one hour. This A PC is fully phosphorylated in vitro by Cdc28 (Fig. 1, showing that Cdc5 is not required for A PC phosphorylation in this in vitro assay. In addition, Cdc5 is not detectable in alpha factor-arrested cells (Hardy and Pautz, 1996; Charles et al., 1998; Shirayama et al., 1998), or in anti-Cdc26 immunoprecipitates of the A PC, isolated from mitotic cells that contain Cdc5 (David Morgan, personal communication; data not shown).

The APC Is Phosphorylated In Vivo

Is the A PC phosphorylated in vivo? Wild-type (ADR 376), CDC27-MBP (ADR 1705), CDC16-my6 (K6180), CDC23-HA (SLJ 378), and cdc5-1 (JC145) were grown overnight in YEP + 2% glucose at 23°C to log phase, arrested in G1 by alpha factor (1 μg/ml) for 3 h, harvested, lysed, and the A PC immunoprecipitated with anti-Cdc26 antibody. The immunoprecipitates were treated with purified Cdc28-His6, Clb2-MBP, Cks1, and [γ-32P]ATP, were washed to remove phosphorylated Clb2-MBP, and were then run on a polyacrylamide gel that was subjected to autoradiography (top) or Western blotting (bottom). cdc5-1 cells were shifted to 37°C for an additional 1 h of alpha factor treatment. A control, cell lysate was mock precipitated in the absence of anti-Cdc26 antibody (no anti-Cdc26) or was precipitated in the presence of anti-Cdc26 antibody, but no Cdc28, Clb2, or Cks1 was added to kinase reaction (no kinase). The Western blot shows that similar amounts of A PC were precipitated with the anti-Cdc26 antibody.
Figure 2. The APC is phosphorylated in vivo. A, APC phosphorylation is greatest in mitosis. Wild-type (A D R 376) and cdc26Δ (L H 307) were grown overnight in Y E P + 2% glucose at 23°C to log phase and then arrested in G1 with alpha factor (1 µg/ml), in S-phase with hydroxyurea (200 mM), or in mitosis with nocodazole (10 µg/ml) for 3 h. Cells were then transferred to phosphate-free CSM + 2% glucose containing 32P04, and alpha factor, HU, or nocodazole as indicated. After 1 h cells were harvested, lysed, and the APC was immunoprecipitated with anti-Cdc26 antibody. Immunoprecipitates were run on a polyacrylamide gel that was subjected to either autoradiography (top) or Western blotting (bottom). B and C, CDC28-VF, clb2Δ, cdc28-1N, and cdc5-1 have reduced APC phosphorylation in vivo. All strains contain pGAL-MPS1. Wild-type (K H 153), CDC28-VF (K H 181), clb2Δ (A D R 1606), cdc28-1N (A D R 1899), cdc5-1 (J C 165), and cdc26Δ (A D R 2023) were grown overnight in Y E P + 2% raffinose at 23°C to log phase, and were then transferred to Y E P + 2% galactose for 4 h to arrest the cells in mitosis by Mps1 overexpression. Cells were then transferred to phosphate-free CSM + 2% galactose containing 32P04, and treated as described in A. In B, cells were arrested by Mps1 overexpression at 23°C, whereas in C cells were arrested at 35°C. In all experiments, the Western blots shown below the autoradiographs illustrate that the same amount of APC was immunoprecipitated in all strains (except for cdc26Δ strains, where no APC was precipitated).
Since Cdc28/Clb complexes are inactive in G1, the differences in APC phosphorylation during different cell cycle stages suggest this reaction depends on Cdc28/Clb complexes. We tested this hypothesis directly by comparing the phosphorylation of the APC in CDC28-VF, clb2Δ, and cdc28-1N cells, three mutants that affect the mitotic activity of Cdc28 (Piggott et al., 1982; Surana et al., 1991; Grandin and Reed, 1993; Rudner et al., 2000). The cells were arrested in metaphase at 25°C (Fig. 2 B) or at 35°C (Fig. 2 C) by overexpressing Mps1 from the galactose inducible GAL1 promoter, which activates the spindle checkpoint. A ll three mutants reduce the phosphorylation of the APC by a factor of 2–4 compared with wild-type.

Previous studies have suggested that in mammalian tissue culture cells, the protein kinase Plk is primarily responsible for phosphorylating the APC (Kotani et al., 1998). A mutant in CDC5, the yeast homologue of Plk, cannot activate the Hct1-dependent APC (Charles et al., 1998). To determine whether the APC phosphorylation is dependent on Cdc5, we examined APC phosphorylation in a cdc5-1 mutant, arrested in metaphase by overexpressing Mps1 at a semirestrictive temperature of 35°C. We observed a similar reduction in APC phosphorylation as in CDC28-VF and cdc28-1N (Fig. 1 C), suggesting that Cdc5 contributes to APC phosphorylation in vivo.

To confirm the identities of the phosphorylated APC subunits and to determine if the APC is phosphorylated by Cdc28 in vivo, we mutated all the potential Cdc28 phosphorylation sites on Cdc16, Cdc23, and Cdc27. Using the weakest possible consensus phosphorylation site (serine or threonine, followed by proline; S/TP) as our criterion, we mutated six sites in Cdc16, one in Cdc23, and five in Cdc27. We refer to the resulting genes as CDC16-6A, CDC23-A, and CDC27-5A. As Fig. 3 A shows, most of the mutated sites fit only the minimal S/TP motif and lack a nearby basic residue found in many biochemically determined Cdk phosphorylation sites (Brown et al., 1999).

We directly assessed the ability of the mutant subunits to be phosphorylated in vivo and in vitro. In vivo, each alanine-substituted subunit is resistant to phosphorylation (Fig. 3 B). This result confirms our conclusion that Cdc16, Cdc23, and Cdc27 are the three major phosphorylated
proteins in the APC (Fig. 2) and shows that among the phosphorylation sites we mutated are the relevant in vivo sites. In addition, the phosphorylation of the different subunits are largely independent of each other. For example, the CDC23-A mutant eliminates the phosphorylation of Cdc23, but not that of Cdc16 and Cdc27. In vitro, Cdc23-A and Cdc27-5A are resistant to phosphorylation in vitro by Cdc28 (Fig. 3 C). Cdc27-HA is still weakly phosphorylated, though much less than the wild-type protein.

Figure 4. The APC associates with Cks1-coupled beads. A, The APC from CDC28-VF associates poorly with Cks-coupled beads. Wild-type (ADR 477) and CDC28-VF (ADR 509) were grown overnight in YEP + 2% glucose at 23°C to log phase and arrested in mitosis with nocodazole (10 μg/ml) for 3 h. Cells were harvested, lysed, and mixed with Cks1-coupled beads. Western blots of the material bound to the Cks1-coupled beads show that the APC and Cdc28/Cib2 bind to the beads. B, Cdc27 phosphorylation can be seen by Western blotting. Wild-type APC, isolated as described in A, was treated either with lambda phosphatase, lambda phosphatase and inhibitors, or inhibitors alone. C, A APC association to Cks1-coupled beads changes through the cell cycle. Wild-type (ADR 1389) and CDC28-VF (ADR 1252) were grown overnight at 30°C in YPD to log phase, arrested in G1 with alpha factor (1 μg/ml), and at t = 0 (alpha factor) the cells were released from the G1 arrest. At t = 75, alpha factor (1.5 μg/ml) was added back to the cultures to rearrest the cells in the next G1. A parallel sample was arrested in mitosis with nocodazole (10 μg/ml). Samples were taken at the indicated times and processed for Western blots (top) or for Cks-coupled bead pulldowns (bottom). The arrow indicates that in wild-type cells when Cib2 levels peak (t = 75), Cdc16 and Cdc27 phosphorylation increases. The bracket indicates that in CDC28-VF cells when Cib2 levels are peaking, Cdc27 phosphorylation decreases. D, A n A PC-containing Cdc27-5A does not bind to Cks1-coupled beads. The strains in Fig. 3 B and CDC28-VF pGAL-MPS1 (KH 181) were grown overnight in YEP + 2% raffinose at 23°C to log phase and then transferred to YEP + 2% galactose for 4 h to arrest the cells in mitosis by Mps1 overexpression. Samples were taken and processed for Western blots (cell lysate), immunoprecipitation with anti-cdc26 antibodies, or Cks1-coupled bead pulldowns as described in Materials and Methods. Equal amounts of lysates were used for the Cks1-coupled bead pulldown and the anti-Cdc26 immunoprecipitation, though a longer exposure is shown for the Cks1-coupled bead pulldown. Cib2 is shown as a loading control. E, Mitotic Cdc28 activity is required for APC phosphorylation. Wild-type (ADR 376), CDC28-VF (ADR 509), cdc28-1N (ADR 483), cdc28-4 (ADR 842), clb2Δ (ADR 313), and cks1-38 (ADR 1767) were grown overnight in YEP + 2% glucose at 23°C to log phase and arrested in mitosis with nocodazole (10 μg/ml) for 3.5 h. Samples were taken at the indicated times and processed for Western blots. Cib3 is shown as a loading control.

The APC Binds to Cks1

During the course of this work we discovered that the budding yeast APC, like the animal APC, can bind to Cks1-coupled beads (Sudakin et al., 1997). This interaction is thought to be critical for APC phosphorylation and reflects the ability of Cks1 to bring Cdc2/Cyclin B complexes into proximity with the APC by interacting with both complexes simultaneously (Patra and Dunphy, 1998; Shtein-
effects G1 activity (expression of Mps1, whereas a mutant that primarily affects Cdc28 activity of Cdc28, whereas a mutant that primarily affects Cdc28 activity. The strains described in Fig. 3 C were grown overnight at 30°C in YEP 8 glucose to log phase, and arrested in G1 with alpha factor (1 μg/ml) for 3 h. The cells were harvested, lysed, and the APC was immunoprecipitated with anti-Cdc26 antibodies, and the in vitro ubiquitination activity of the immunoprecipitates was measured. Fig. 5 shows that in vitro ubiquitination assay that uses an iodinated fragment of sea urchin cyclin B as a substrate and the APC provided from anti-Cdc26 immunoprecipitates (Charles et al., 1998). Fig. 5 shows that there is no difference in G1-specific APC activity between wild-type cells and those carrying alanine mutations in APC subunits (CDC16-6A, CDC23-A, or CDC27-5A). Thus, the mutations in putative CDC28-VF-dependent phosphorylation sites have not disrupted the ability of these subunits to associate with other APC components or produce normal levels of Hct1-dependent APC activity.
A PC activity. In addition, cells carrying alanine-substituted A PC subunits show no obvious growth defects at any temperature.

We asked if the alanine substitutions in the A PC, like CDC28-VF, have difficulty leaving mitosis (Rudner et al., 2000). Wild-type and CDC16-6A CDC23-A CDC27-5A cells were arrested in G1 by the mating pheromone alpha factor and then released into the cell cycle. Once cells had budded, alpha factor was readded to arrest cells that had completed the cycle. CDC16-6A CDC23-A CDC27-5A cells show a 20-min delay in sister chromatid separation (Fig. 6 A). Cib2 and Cib3 proteolysis are delayed by >40 min. This defect is not due to slower mitotic entry, because wild-type and CDC16-6A CDC23-A CDC27-5A cells initiate budding, degrade Sic1, and form a short mitotic spindle at the same time (Fig. 6 A and data not shown).

Figure 6. The alanine-substituted A PC delays in mitosis and is sensitive to spindle checkpoint-dependent arrest. A, Wild-type (ADR2061) and CDC16-6A CDC23-A CDC27-5A (ADR2064) were grown overnight at 23°C in YPD to mid log phase, arrested in G1 with alpha factor (1 μg/ml), and at t = 0 the cells were released from the G1 arrest. At t = 80, alpha factor (1.5 μg/ml) was added back to the cultures to rearrest the cells in the next G1. Top, Samples were taken at the indicated times and processed for Western blots. Bottom left, Sister chromatid separation was scored by counting the number of fluorescent spots (one or two) of green fluorescent protein (GFP)-lacI bound to 256 tandem repeats of lacO integrated at the LEU2 locus. Bottom right, Spindles were visualized by indirect immunofluorescence of formaldehyde-fixed cells probed with an antialpha-tubulin antibody. B, All strains contain pGAL-MPS1. Wild-type (K153), CDC28-VF (K181), CDC23-A (ADR1973), CDC27-5A (ADR1974), CDC16-6A (ADR1975), CDC23-A CDC27-5A (ADR1976), CDC16-6A CDC23-A (ADR1977), CDC16-6A CDC27-5A (ADR1978), and CDC16-6A CDC23-A CDC27-5A (ADR1979) were grown to saturation for 2 d in YEP + 2% glucose at 30°C, diluted tenfold, and fourfold serial dilutions were prepared in a multiwell dish and spotted onto YEP + 2% glucose (left) or YEP + 1% galactose (right). The plates were incubated at 30°C for 2 d.

Mutating A PC phosphorylation sites also causes an increased sensitivity to spindle checkpoint arrest caused by Mps1 overexpression (Hardenick et al., 1996; Rudner et al., 2000). Serial dilutions of wild-type, CDC28-VF, mutants in single A PC subunits, double mutants, and the triple mutant were spotted on plates where Mps1 is induced to high levels (Fig. 6 B). Both CDC16-6A and CDC27-5A are sensitive to Mps1 overexpression and combining the two mu-
tants creates a phenotype similar to that of CDC28-VF. The CDC23-A mutation alone has little phenotype, but exacerbates the effect of both the CDC16-6A and CDC27-5A mutations. These data suggest that phosphorylation of the APC subunits contribute to the ability to overcome the spindle checkpoint and suggest that the alanine-substituted APC, like CDC28-VF, may be defective in the Cdc20-dependent APC.

To test Cdc20-dependent APC function more directly, we examined the ability of these nonphosphorylatable APC mutants to support Pds1 degradation in vivo. Pds1 is normally unstable in anaphase with a half-life of about ten minutes (Jaspersen et al., 1998). We arrested wild-type and nonphosphorylatable APC mutants in anaphase (using the cdc15-2 mutant), induced Pds1 expression from the GAL1 promoter by adding galactose for one hour, and then shut the promoter off by adding glucose and examined the rate of Pds1 degradation.

Previously, we have shown that in this anaphase arrest, CDC28-VF and cdc20Δ stabilize Pds1 (Rudner et al., 2000). We see a similar effect when the CDC27-5A and CDC16-6A mutations are combined with cdc15-2. The half life of Pds1 is increased to 30 min in anaphase-arrested CDC27-5A, and to >90 min in CDC16-6A cells (Fig. 7A).

We also have examined the association of Cdc20 with the APC in the alanine-substituted mutants at the cdc15-2 block, a time when the Cdc20-dependent APC is active. This association is impaired in CDC28-VF (Rudner et
We arrested cdc15-2, cdc15-2 CDC16-6A, and cdc15-2 CDC27-5A cells in anaphase, immunoprecipitated the A PC with anti-Cdc26 antibodies, and examined the amount of associated Cdc20. The association of Cdc20 to the A PC is reduced in CDC27-5A cells and severely impaired in CDC16-6A cells (Fig. 7 B).

The Role of Cdc5 in APC Phosphorylation

Different groups debate whether Cdc2 (Cdk1) or Plk is the major A PC kinase in vivo (Lahav-Baratz et al., 1995; Kotani et al., 1998; Patra and D unphy, 1998; Sh teinberg and H ersh, 1999; Sh teinberg et al., 1999). Since we find that A PC phosphorylation is reduced in a cdc5-1 mutant (Fig. 2 C), we tested whether purified recombinant Cdc5 could phosphorylate the A PC in vitro. Like Cdc28, Cdc5 phosphorylates Cdc16, Cdc27, and Apc9 (Fig. 8 A), but unlike Cdc28, appears to not phosphorylate Cdc23. Cdc5 also phosphorylates proteins that have the molecular weights of several other A PC subunits (A pc1,-2,-4, and -5; Zachariae et al., 1996). We have not confirmed the identity of these proteins because there is little evidence that these proteins are major targets of phosphorylation in vivo (Fig. 2). The ability of human Plk to activate the A PC in vitro depends on pretreatment with Cdc2/Cyclin B complexes (Kotani et al., 1998), a result that has been interpreted to suggest that Cdc2 activates Plk’s kinase activity against the A PC. In our hands, however, Cdc5’s ability to phosphorylate the A PC does not increase when the kinase is pretreated with purified Cdc28/CDC16-6A, and Cdc5 phosphorylates the A PC with anti-Cdc26 antibodies, and examined the amount of associated Cdc20. The association of Cdc20 to the A PC is reduced in CDC27-5A cells and severely impaired in CDC16-6A cells (Fig. 7 B).

We next tested whether purified Cdc5 can phosphorylate the alanine-substituted A PC. The Cdk sites we mutated on Cdc16, Cdc23, and Cdc27 are also potential sites of phosphorylation by Cdc5. Substrates of the frog homologue of Cdc5, Plx1, become epitopes for the MPM-2 antibody after phosphorylation by Plx1 (Kumagai and Dunphy, 1996) and MPM-2 recognizes phosphorylation at SP or TP sites (Westendorf et al., 1994). In contrast to their effect on phosphorylation by Cdc28, the A PC phosphorylation site mutants had no effect on in vitro phosphorylation of the A PC by recombinant Cdc5 (Fig. 8 B). This observation makes it likely that the reduced in vivo A PC phosphorylation seen in cdc5-1 cells is an indirect effect of reduced Cdc5 activity, rather than a direct in vivo phosphorylation of these A PC subunits by Cdc5.

Discussion

We have shown that the budding yeast A PC subunits, Cdc16, Cdc23, and Cdc27, are phosphorylated in vivo and in vitro. Phosphorylation in vivo depends on Cdc28, and in vitro it is catalyzed by pure Cdc28/Cdc23/Cdc27-Cdc28 complex. Mutating potential Cdc28 phosphorylation sites in Cdc16, Cdc23, and Cdc27 abolishes their in vivo phosphorylation and compromises the mitotic, but not the G1 functions of the A PC. We have also shown that Cdc5 affects A PC phosphorylation in vivo and can catalyze A PC phosphorylation in vitro. Our analysis of A PC phosphorylation site mutants in vivo and in vitro, however, argues that in vivo Cdc5 indirectly induces the phosphorylation of Cdc16,
Cdc23, or Cdc27, rather than directly modifying these subunits.

The APC Is Phosphorylated in Budding Yeast

Our results agree with studies on other organisms that show mitosis-specific APC phosphorylation. Cdc16, Cdc23, Cdc27, and Apcl are phosphorylated in frogs; Apcl, Cdc16, and Cdc27 are phosphorylated in mammalian tissue culture cells; and Cdc16 (Cut 9) is phosphorylated in fission yeast (Peters et al., 1996; Yamada et al., 1997; Patra and Dunphy, 1998; Kotani et al., 1999). Although a PC phosphorylation has been shown to activate the Cdc20-dependent APC in mammalian tissue culture and clam egg extracts (Kotani et al., 1998; Sheinberg et al., 1999), and Cks1 depletions prevent mitotic exit in frog extracts (Patra and Dunphy, 1996), this is the first report to examine the in vivo function of an APC phosphorylation. A through phosphorylation of Cdc16, Cdc23, and Cdc27 is not essential for viability in budding yeast, our studies suggest that it stimulates Cdc20-dependent APC activity and Cdc20 binding to the APC in vivo.

Cdc27 remains partially phosphorylated in G1 cells (Fig. 4 C). The presence of slower migrating Cdc27 in G1 cells could arise two ways: during the exit from mitosis, if Cdc28-catalyzed phosphorylation declines after phosphorylation has been shown to activate the Cdc20-dependent APC in mammals; or in G1, by phosphorylation catalyzed by another kinase. Because Cdc27-5A runs as a single band on Western blots in G1 (Fig. 5), we favor the possibility that G1 phosphorylation on Cdc27 remains from the previous mitosis. This finding would suggest that the phosphatase that removes phosphorylation from the APC is only active in mitosis. PP2A has been proposed to play such a role in clams and frogs (Lahav-Baratz et al., 1995; Vorlauffer and Peters, 1998).

In one report, Plk has been identified as the major kinase of the mammalian APC (Kotani et al., 1998), although these have argued that this role is played by Cdc2 (Lahav-Baratz et al., 1995; Patra and Dunphy, 1998; Sheinberg and Hershko, 1999; Sheinberg et al., 1999). We asked if its budding yeast homologue, Cdc5, plays a similar role. In vivo, an APC phosphorylation is reduced in the cdc5-1 mutant and purified Cdc5 phosphorylates the APC in vitro (Figs. 2 C and 8 A). Three observations argue that in living cells Cdc5 does not directly phosphorylate the APC subunits we have studied: phosphorylation site mutations that completely block phosphorylation of Cdc16, Cdc23, and Cdc27 in vivo, do not block in vitro phosphorylation of these subunits by Cdc5 (Fig. 8 B); purified Cdc28/Cdc2/Cks1, that lacks detectable Cdc5, efficiently phosphorylates immunoprecipitated APC (Fig. 1); and the same mutations that block Cdc28-catalyzed phosphorylation in vitro also block in vivo APC phosphorylation (Fig. 3).

If Cdc5 does not phosphorylate Cdc16, Cdc23, and Cdc27 directly, how does it regulate the phosphorylation of these subunits? Cdc5 may be responsible for phosphorylating other APC subunits (Apcl, -2, -4, and -5 are potential substrates; Fig. 8) in vivo, and the phosphorylation of these subunits may affect the phosphorylation of the Cdc28 targets Cdc16, Cdc23, and Cdc27. Alternatively, Cdc5 may modulate Cdc28/Cdc2/Cks1 activity or localization.

Phosphorylation Stimulates Cdc20-dependent APC Activity

We have shown that phosphorylation site mutants in the APC reduce activation of the Cdc20-dependent APC. The half-life of Pds1 is increased in CD C27-5A and CD C16-6A cells, and this defect in Cdc20 function could be explained by the observed inability of Cdc20 to bind an APC containing Cdc16-6A. This data supports genetic experiments showing that reduced mitotic Cdc28 activity compromises the Cdc20-dependent APC (Rudner et al., 2000).

If Cdc20 binding and activity depend on a phosphorylated APC, why is the triple mutant CD C16-6A CD C23-A CDC27-5A viable? Even in the triple mutant there is some residual Cdc20 binding to the APC (data not shown), which is presumably sufficient to drive the metaphase to anaphase transition. The residual binding of Cdc20 to the APC could depend on the phosphorylation of other subunits. In support of this idea, we see weak phosphorylation of proteins we believe to be Apcl, -4, -5, and -9 in some in vitro labelings (data not shown), and a protein we believe to be Apcl is phosphorylated in vitro by Cdc28/Cdc2/Cks1 complexes (data not shown and Fig. 1; Zachariae et al., 1996). In addition, Cdc28-1N, a mutation in Cdc28 that cannot bind Cks1 (Kaiser et al., 1999; and data not shown) and cks1-38, have reduced APC phosphorylation (Figs. 1 C and 4 E). These two mutants are temperature-sensitive for growth and arrest in mitosis (Piggott et al., 1982; Tang and Reed, 1993), suggesting that APC phosphorylation may be essential. Alternatively, it has been proposed that the primary defect in cdc28-1N and cks1-38 is in proteasome function (Kaiser et al., 1999), though proteasome activity was examined in G1, not in mitosis, leaving the relevance of this finding to the exit from mitosis uncertain.

Our data suggests that activation of the APC by phosphorylation opposes its inhibition by the spindle checkpoint. Although CD C16-6A CD C23-A CD C27-5A is viable, its delay in mitosis (Fig. 6 A) becomes lethal when the spindle checkpoint is activated (Fig. 6 B). Both APC phosphorylation and the spindle checkpoint affect the ability of Cdc20 to activate the APC, but have no effects on the G1, Hct1-dependent activity of the APC.

Regulation of APC Phosphorylation

Phosphorylation of the APC in frogs and clams in vitro depends on homologues of the small Cdk binding protein, Cks1, and in clams, Cks1 stimulates Cdc20-dependent APC activity (Patra and Dunphy, 1998; Sheinberg and Hershko, 1999; Sheinberg et al., 1999). In budding yeast, the role of Cks1 remains uncertain. Although we add purified Cks1 to our in vitro kinase reactions, Cks1 is not required for APC phosphorylation in vitro (Fig. 1 and data not shown). However, APC phosphorylation in vivo clearly depends on Cks1 (Fig. 4 E) and phosphorylation of Cdc27 is required for APC binding to Cks1-coupled beads (Fig. 4 D). We do not think that the binding of the APC to Cks1-coupled beads correlates with the ability of Cdc28 to phosphorylate the APC in vivo: although an APC containing Cdc27-5A does not bind to Cks1-coupled beads, Cdc16 and Cdc23 are fully phosphorylated in a CDC27-5A mutant. Despite this in vivo finding, we do see reduced in

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vitro phosphorylation of Cdc16 and Cdc23 in an A PC containing Cdc27-5A (Fig. 3 C).

Mutants that affect the mitotic form of Cdc28 have reduced levels of phosphorylation of the A PC, whereas cdc28-4 cells, which are defective in the G1 form of Cdc28 (Reed, 1980), show normal phosphorylation of Cdc27 and Cdc16. We were surprised to discover that A PC phosphorylation in cdc28-4 appears to be normal (Fig. 4 E), because this mutant has ~20% the amount of Cdc28 protein as wild-type cells at the permissive temperature of 23°C, and very little detectable Cdc28-associated kinase activity when immunoprecipitated from cell lysates (Surana et al., 1991; and data not shown). A possible explanation of the absence of mitotic defects in cdc28-4 cells is that the specific activity of each Cdc28-4 molecule is equal to that of wild-type Cdc28, although the total number of active kinases is drastically reduced. The specific activity of individual Cdc28 molecules may be critical for A PC phosphorylation because one Cdc28/Ctb2/Cks1 complex may bind persistently to the A PC. Once bound to the A PC, this single complex might be responsible for multiple phosphorylations. If the steady state phosphorylation of the A PC is determined by the balance between phosphorylation by Cdc28 and dephosphorylation by protein phosphatases, and Cdc28 remains bound to the A PC, a drop in specific activity of Cdc28 would reduce the phosphorylation and activity of the A PC.

How do cells escape from mitosis? If activating Cdc28/Ctb2/Cks1 complexes activates the Cdc20-dependent A PC, which in turn triggers chromosome segregation, how do cells ensure that the lag between activating Cdc28 and activating the Cdc20-dependent A PC is long enough to assemble a spindle and align chromosomes on it? A likely answer is that the spindle checkpoint inhibits Cdc28 in cells with misaligned chromosomes (Hwang et al., 1998; K im et al., 1998), this explanation is not enough. Inactivating the spindle checkpoint does not kill yeast cells, implying other mechanisms exist to block premature activation of the Cdc20-dependent A PC. Another possible mechanism is regulating the abundance of Cdc20. High levels of CD C20 transcripts are restricted to mitotic cells and A PC-dependent proteolysis restricts the abundance of Cdc20 (Weinstein, 1997; Kramer et al., 1998; Prinz et al., 1998; Shirayama et al., 1998). None of these forms of regulation exist in early frog embryos, where Cdc20 (Fizzy) levels are constant through the cell cycle and spindle depolymerization does not induce mitotic arrest (Minshull et al., 1994; Lorca et al., 1998). In addition, overexpressing Cdc20 in budding yeast raises the level of Cdc20 mRNA and protein, but does not advance the exit from mitosis, suggesting other mechanisms must exist to regulate Cdc20-dependent A PC activity (Prinz et al., 1998). Regulating the rate of Cdc28-catalyzed A PC phosphorylation provides an additional mechanism. If this phosphorylation were slow relative to spindle assembly, most cells would manage to align their chromosomes on the spindle before activating the Cdc20-dependent A PC, which in turn induces Pds1 destruction and anaphase.

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Note Added in Proof. Similar results showing that Cdc20 only binds to a phosphorylated A PC have been published recently (Kramer, E.R., N. Scheuringer, V. Podrelejnikov, M. Mann, and J.M. Peters. 2000. Mol. Biol. Cell. 11:1555–1569).

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