Chk1 Kinase Negatively Regulates Mitotic Function of Cdc25A Phosphatase through 14-3-3 Binding

Mei-Shya Chen, Christine E. Ryan and Helen Piwnica-Worms

Chk1 Kinase Negatively Regulates Mitotic Function of Cdc25A Phosphatase through 14-3-3 Binding

Mei-Shya Chen,1,2† Christine E. Ryan,1,2 and Helen Piwnica-Worms1,2,3*

Howard Hughes Medical Institute, 1 Department of Cell Biology and Physiology, 2 Department of Internal Medicine, 3 Washington University School of Medicine, St. Louis, Missouri 63110-1093

Received 16 April 2003/Returned for modification 20 June 2003/Accepted 21 July 2003

The order and fidelity of cell cycle events in mammals is intimately linked to the integrity of the Chk1 kinase-Cdc25A phosphatase pathway. Chk1 phosphorylation targets Cdc25A for destruction and, as shown here, inhibits interactions between Cdc25A and its mitotic substrate cyclin B1-Cdk1. Phosphorylation of Cdc25A on serine 178 and threonine 507 facilitates 14-3-3 binding, and Chk1 phosphorylates both residues in vitro. Mutation of T507 to alanine (T507A) enhanced the biological activity of Cdc25A. Cdc25A(T507A) was more efficient in binding to cyclin B1, activating cyclin B1-Cdk1, and promoting premature entry into mitosis. We propose that the Chk1/Cdc25A/14-3-3 pathway functions to prevent cells from entering into mitosis prior to replicating their genomes to ensure the fidelity of the cell division process.

The Cdc25A protein phosphatase positively regulates the cell cycle by activating cyclin-dependent protein kinases (Cdks). Cdc25A was identified as a potential human oncogene based on its ability to transform primary mouse embryo fibroblasts in cooperation with activated Ras or loss of RB (14). In addition, Cdc25A is overexpressed in a variety of human cancers (5, 6, 15, 34), and in many cases, Cdc25A overexpression is a poor prognostic indicator. Overexpression of Cdc25A is required for efficient induction of S-phase entry (4, 44), and microinjection of antibodies against Cdc25A is a major regulator of Cdc25A phosphorylation in vivo. Here we identify additional Cdc25A phosphorylation sites and report a novel mechanism of Chk1-mediated Cdc25A regulation involving 14-3-3 proteins.

Human Cdc25A is phosphorylated at several sites in vivo, and Chk1 is required for the majority of these phosphorylations in vivo during interphase (57). Chk1 phosphorylates Cdc25A to promote its ubiquitin-mediated proteolysis (11, 16, 20, 46, 57). Chk1 also promotes the degradation of Cdc25A in Xenopus laevis (26, 45). In vitro, Chk1 phosphorylates human Cdc25A at several sites, and phosphorylation of these residues requires Chk1 in vivo (46, 57). These findings argue that Chk1 is a major regulator of Cdc25A phosphorylation in vivo. Here we identify additional Cdc25A phosphorylation sites and report a novel mechanism of Chk1-mediated Cdc25A regulation involving 14-3-3 proteins.

MATERIALS AND METHODS

Antibodies. Cdc25A was detected with antibodies purchased from Santa Cruz and Upstate Biotechnology, Inc. (UBI). Cdc25A fusion proteins were precipitated with anti-c-Myc(9E10)-agarose conjugate and detected by Western blotting with c-Myc polyclonal antibody (Santa Cruz). Anti-Cdc25A antibodies were raised against the 14-3-3 binding sites of Cdc25A, and Chk1 is required for the majority of these phosphorylations in vivo during interphase (57).

Generation of tTA-regulated adenoviruses. An XhoI/HindIII fragment of pUHD10-3 (17, 40), containing seven repeats of the tetracycline operator linked to a cytomegalovirus minimal immediate-early promoter, was used to transduce adenoviruses. Recombinant adenoviruses were generated by homologous recombination. Recombinant adenoviruses were generated and propagated in 293 cells using the pAdEasy system as described previously (21). Expression of Cdc25A is regulated by the tetracycline transactivator (tTA), with recombinant adenovirus encoding tTA (24).

14-3-3 binding assays. Transfected Cos3 or 293 cells infected with recombinant adenoviruses were suspended in buffer A (10 mM Tris-HCl [pH 7.5], 5 mM MgCl2, 1 mM EGTA, 25 mM NaF) supplemented with 1 mM dithiothreitol (DTT) and the following inhibitor cocktail: 1 μM microcin, 1 mM sodium orthovanadate, 2 mM phenylmethylsulfonyl fluoride (PMSF), 0.15 U of aprotinin per ml, 20 μM leupeptin, and 20 μM pepstatin. Cells were lysed by passage through a 25-gauge needle 30 times. Precleared lysates were incubated with...
anti-c-Myc(9E10)–agarose, and Cdc25A precipitates were washed in buffer A. Proteins were resolved by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) and analyzed for Myc-Cdc25A and 14-3-3 proteins by Western blotting.

Far-Western analysis. HeLa cells cotransfected with recombinant adenoviruses encoding rTA and Myc-tagged versions of wild-type (wt) and mutant Cdc25A proteins were lysed in mammalian cell lysis buffer (MCLB; 50 mM Tris-HCl [pH 8.0], 150 mM NaCl, 0.5% NP-40, 5 mM EDTA, 2 mM DTT, 1 mM sodium orthovanadate, 10 mM β-glycerophosphate, 1 mM NaF, 1 μM microcystin, 1 mM PMSF, 5 μg of leupeptin per ml, and 10 μg of aprotinin per ml). Clarified supernatants were incubated with anti-c-Myc(9E10)–agarose conjugate. Precipitates were resolved by SDS-PAGE and transferred to Hybond-P membranes (Amersham). Membranes were blocked in 5% milk–TBS (10 mM Tris [pH 8.0], 150 mM NaCl) overnight at 4°C and then washed in TBS. Washed membranes were incubated in 0.1% of GST–14-3-3ε peptide for 2 h at room temperature. Membranes were washed and blocked as described above. Peptide (0.1 mM) was incubated with 0.1% of GST–14-3-3ε peptide in TBS containing 1 mg of BSA per ml for 2 h at room temperature. Membranes were then incubated in the peptide–GST–14-3-3ε mixture overnight at 4°C. Membranes were washed in TBS, incubated with antibodies specific for GST, and processed as described above. The peptides used for the competition assays were as follows: PHCVPRDDLSELEANCLCP (38, 48) and phosphorylated and unphosphorylated forms of C-TQQRNS178APAR and C-RTKSRT507WAGE. In addition, two phosphopeptides lacking 14-3-3 consensus sequences were used. The pT68 phosphopeptide from Chk2 consists of the sequence C-ETVSpT68QELYS, and the pS123 phosphopeptide from Cdc25A consists of the sequence C-LKRSHpS123DSLD.

siRNA experiments. The small interfering RNA (siRNA) oligonucleotide corresponding to nucleotides 127 to 147 of the human Chk1 coding region (57) was synthesized by Bacteron Research, Inc. The control siRNA duplex was designed on a target sequence of 5′-GGCGCGTTTGTAGGATCGC-3′. siRNA duplexes were transfected into HeLa cells using Oligofectamine (Invitrogen) according to the manufacturer’s recommendations. Twenty-four hours after transfection, cells were cotransfected with adenoviruses encoding rTA and Myc-tagged versions of wt and mutant Cdc25A proteins. Cells were harvested 9 h after infection by lysing in MCLB. Proteins were resolved by SDS-PAGE and analyzed by Western blotting.

Double thymidine block and release protocol. To synchronize HeLa cells at the G2/S border, cells were treated with 2 mM thymidine for 16 to 19 h. Cells were released from the block by washing with phosphate-buffered saline (PBS), followed by trypsinization and resuspending into complete growth medium containing 10% FCS, 2 mM L-glutamine, and 2 mM g-mercaptoethanol. After 8 h to 9 h, thymidine was added to the medium to a final concentration of 2 mM, and cells were cultured for an additional 16 to 18 h. Cells were then rinsed twice with PBS and cultured in complete growth medium.

Overproduction of Cdc25A proteins in S phase. HeLa cells were synchronized using a double thymidine block and release protocol. Four hours before release from the second block, cells were cotransfected with adenoviruses encoding rTA and GFP (control) or rTA and Myc-tagged versions of wt and mutant Cdc25A proteins. Infections were carried out at a multiplicity of infection of 5 to 10. Cells were harvested by trypsinization 3 h after release from the second block. A portion of the cells was analyzed as described above. A portion of the cells was analyzed by flow cytometry to determine the percentage of cells in S phase. A portion of the cells was harvested at 3 h after release and analyzed for Cdc25A protein by Western blotting.

Phosphatase assays using bacterial GST fusion proteins and Cdk1/cyclin B1 complexes. DH5α cells were transfected with plasmids encoding GST fusions of Cdc25A (wt and mutants), were grown at 37°C to an A600 of 0.6, and isopropyl-1-thio-β-D-galactopyranoside (IPTG) was added to a final concentration of 1 mM. After growing for an additional 2 h at 37°C, cells were pelleted by centrifugation. Cell pellets were washed twice with PBS and then suspended in STE (10 mM Tris-HCl [pH 8.0], 100 mM NaCl, 1 mM EDTA) containing 1% Triton X-100, washed twice with STE, and suspended in buffer A (20 mM Tris-HCl [pH 7.5], 1 mM EDTA, 150 mM NaCl, 1 mM DTT, 1 mM EDTA) containing 1% Triton X-100 and protease inhibitors (2 μM PMSF, 0.5 μg of aprotinin per ml, and 0.4 μg leupeptin). After washing, cells were lysed by incubation with 0.5% NP-40. The supernatants were incubated with anti-c-Myc(9E10)–agarose beads (Sigma Chemical Co.) and washed twice with STE, twice with buffer A, and twice with buffer B containing 1% NaCl. Fractions containing phosphorylated Cdk1/cyclin B1 complexes were pooled, dialyzed in a solution containing 20 mM Tris (pH 7.4), 2 mM DTT, and 10% glycerol, and frozen at −80°C.

Downloaded from http://mcb.asm.org/ on January 6, 2014 by Washington University in St. Louis

Chk1/Cdc25A/14-3-3 PATHWAY 7489

VOL. 23, 2003

Chk1/Cdc25A/14-3-3 PATHWAY 7489

VOL. 23, 2003
and then were suspended in 75 μl of phosphatase buffer. Five microliters of Cdc25A immobilized on Myc-agarose was suspended in 20 μl of phosphatase buffer. Reactions were incubated at 30°C for 10, 15, or 20 min after the addition of 5 μl of cyclin B1/Cdk1 substrate. Samples were processed for histone H1 kinase assays as described above. The remaining Cdc25A precipitates were immunoblotted and quantified by using Myc antibodies, ECF reagents, and the Storm 860 imaging system. Histone H1 kinase activities were normalized for levels of Cdc25A in each reaction.

Phosphatase assays using mFP. The levels of GST fusion proteins were estimated by comparison to a BSA standard after SDS-PAGE and Coomassie blue staining or were quantified by using ECF reagents and the Storm 860 imaging system. Immunoblotting was performed with antibody specific for GST together with alkaline phosphatase (AP)-conjugated anti-rabbit immunoglobulin G (Jackson ImmunoResearch). Proteins were visualized by chemiluminescence.

Approximately 10 μg of purified GST-Cdc25A (wt and mutants) was incubated in 500 μl of buffer consisting of 50 mM Tris, 50 mM Bis-Tris, 100 mM sodium acetate (pH 6.5), 0.01% Tween 20, 1 mM DTT, and 62.5 μM 3-O-methyl fluorescein phosphate (mFP) (Sigma) at room temperature as described previously (49). Reactions were followed by spectroscopy at 477 nm. All experiments were done in triplicate.

Phosphorylation of S178 and T507 as a function of the cell cycle. HeLa cells synchronized by a double thymidine block were infected with adenoviruses encoding Myc-tagged Cdc25A and tTA. G1/S-arrested cells were collected prior to release from the second block, S-phase cells were collected at 3 h after release from the block, and mitotic cells were obtained by infecting cells immediately after release from the block in medium containing nocodazole for 10 h.

Additional methods. Cdc25A mutants were generated by a PCR-based strategy or by use of the QuickChange XL site-directed mutagenesis kit (Stratagene) and were verified by sequencing.

Chk1 and Chk2 kinase reactions were carried out in vitro with bacterially produced His-Cdc25A and insect cell-produced GST-tagged Chk1 and Chk2 as described previously (19, 57).

RESULTS

Phosphorylation of Cdc25A at S178 and T507 mediates the binding of 14-3-3 proteins to Cdc25A. 14-3-3 proteins were isolated in a two-hybrid screen using human Cdc25A as bait (8). A mutagenesis strategy was employed to identify residues in Cdc25A that confer 14-3-3 binding (Fig. 1A). 14-3-3 bound independently to both the N (amino acids 1 to 336) and C (amino acids 389 to 524) termini of Cdc25A. Substitution of alanine for serine 178 (S178A) eliminated binding to residues 1 to 336 and substitution of alanine for threonine 507 (T507A) eliminated 14-3-3 binding to residues 389 to 524. Full-length Cdc25A proteins substituting alanine for S178, T507, or both
were generated and tested for 14-3-3 binding. Complete loss of 14-3-3 binding was seen when both S178 and T507 were replaced with alanine (Fig. 1B, lane 5). Thus, both S178 and T507 are required for interactions between Cdc25A and 14-3-3 proteins. The phosphatase activity of Cdc25A was not absolutely required for 14-3-3 binding, as a catalytically inactive form of Cdc25A (C430S) was capable of binding to 14-3-3 proteins (Fig. 1B, lane 6).

14-3-3 binding to target proteins is, in general, mediated by phosphorylation (33, 54). Phosphorylation of Cdc25A at S178 and T507 in vivo was confirmed using phospho-specific antibodies (Fig. 2A). In addition, mutation of S178 did not affect phosphorylation of T507 nor did mutation of T507 affect phosphorylation of S178. Given that phosphorylation of Cdc25A in vivo is absolutely dependent on Chk1, we predicted that Chk1 would phosphorylate Cdc25A at S178 and T507 in vitro (57). As seen in Fig. 2B, Chk1 phosphorylated both residues in vitro (lanes 1 to 3). Interestingly, the Chk2 protein kinase, which has been proposed to regulate Cdc25A following IR (11), was incapable of phosphorylating Cdc25A at T507 in vitro (Fig. 2B, lanes 4 to 6). Next, the phosphorylation of Cdc25A at T507 and S178 was examined in cells in which Chk1 levels had been reduced by Chk1-specific siRNAs. As seen in Fig. 2C, Chk1 but not β-catenin levels were significantly reduced in cells treated with Chk1-specific siRNAs (lanes 2 and 4). Levels of both Cdc25A (lane 2) and Cdc25A(S178A/T507A) (lane 4) were higher in cells in which Chk1 levels had been reduced by siRNA treatment. This result is consistent with our previous work demonstrating that Chk1 negatively regulates the stability of Cdc25A during an unperturbed cell cycle (57). Importantly, even though Cdc25A levels were elevated in cells lacking Chk1, reactivity of Cdc25A with the pT507 antibody was significantly reduced (lane 2) relative to reactivity of Cdc25A in cells containing Chk1 (lane 1). Loss of Chk1 did not affect S178 phosphorylation as dramatically as T507 phosphorylation. These results support the conclusion that Chk1 is the major T507 kinase but that kinases in addition to Chk1 regulate S178 phosphorylation. This is consistent with the results in Fig. 2B showing that Chk2 is capable of phosphorylating Cdc25A at S178 but not T507 in vitro.
Far Western analysis was performed to determine if binding of 14-3-3 protein to wt and mutant forms of Cdc25A was direct. As seen in Fig. 3A, 14-3-3 bound directly to Cdc25A (lane 1) but poorly to the S178A (lane 2) and S178A/T507A (lane 4) mutants. Furthermore, peptides containing phosphorylated S178 (Fig. 3B, lane 4) or T507 (Fig. 3B, lane 6, and Fig. 3C, lane 3) competed for 14-3-3 binding, as did an unphosphorylated peptide (Fig. 3B and C, lanes 2) that binds to 14-3-3 proteins (38, 48). The unphosphorylated S178 and T507 peptides did not compete efficiently in this assay, nor did phosphopeptides lacking 14-3-3 consensus motifs (Fig. 3C). These results demonstrate that 14-3-3 binds directly to Cdc25A and that phosphorylation of S178 and T507 mediates this interaction.

14-3-3 binding mutants induce a mitotic-like state in S-phase cells. A high percentage of abnormal chromosome spreads were observed in S-phase cells expressing the T507A or S178A/T507A mutant (Fig. 4B and C). Furthermore, peptides containing phosphorylated S178 and/or T507 competed for 14-3-3 binding, as did an unphosphorylated peptide (Fig. 3B and C, lanes 2) that binds to 14-3-3 proteins (38, 48). The unphosphorylated S178 and T507 peptides did not compete efficiently in this assay, nor did phosphopeptides lacking 14-3-3 consensus motifs (Fig. 3C). These results demonstrate that 14-3-3 binds directly to Cdc25A and that phosphorylation of S178 and T507 mediates this interaction.

Cdc25A or Cdc25A(S178A) stained positive for phospho-histone H3, whereas the percentage staining positive for phospho-histone H3 increased significantly in cells expressing the T507A (29.1%) or S178A/T507A (28.0%) mutant. Failure to observe cells with DNA contents of less than 2N indicates that the 14-3-3 binding mutants did not induce S-phase cells to undergo apoptosis.

**Phosphorylation of Cdc25A on T507 negatively regulates the ability of Cdc25A to dephosphorylate Cdk1.** Phosphatase assays were performed to monitor the ability of each Cdc25A mutant to dephosphorylate and activate cyclin B1/Cdk1 in vitro. To verify that mutation of S178 and/or T507 did not affect the intrinsic phosphatase activity of Cdc25A, the activity of bacterially produced Cdc25A was examined, because bacterial Cdc25A is neither phosphorylated nor bound to 14-3-3 proteins. Mutation of S178 and T507 either alone or together did not affect the activity of bacterially produced Cdc25A (Fig. 6A). Next, HeLa cells were infected with adenoviruses encod-
ing GFP, Cdc25A, or mutant forms of Cdc25A. Cells were subjected to FACS analysis at the time of harvest to verify that cell cycle profiles were identical (data not shown). wt and mutant forms of Cdc25A were isolated from infected cells and assayed for the ability to activate Cdk1 in vitro. HeLa cell-derived Cdc25A, unlike bacterially derived protein, is phosphorylated and bound to 14-3-3 proteins. The T507A and S178A/T507A mutants consistently showed an approximately twofold increase relative to wt Cdc25A in the ability to activate cyclin B1/Cdk1 in vitro (Fig. 6B). The activity of Cdc25A(S178A) was modestly increased over that of wt Cdc25A. Furthermore, higher levels of cyclin B1/Cdk1 were observed to coprecipitate with the 14-3-3 binding mutants of Cdc25A than with wt Cdc25A (Fig. 7B).

The C terminus of Cdc25A contains a cyclin B1/Cdk1 docking site. Taken together, these results suggest that phosphorylation of T507 and subsequent 14-3-3 binding to the C terminus of Cdc25A negatively regulates interactions between Cdc25A and cyclin B1/Cdk1. Cdc25B has a cyclin/Cdk docking site within its C terminus (49), and Cdc25A, but not Cdc25C, conserves many of these residues (Fig. 7A). To test whether the C terminus of Cdc25A conferred cyclin B1/Cdk1 binding, mutations in the putative binding domain were generated and mutants were tested for the ability to bind to cyclin B1/Cdk1 (Fig. 7C). Mutation of K514 and R520 severely impaired the ability of Cdc25A to bind to cyclin B1/Cdk1.

If the T507A and S178A/T507A mutants obtain their biological potency by enhanced binding to cyclin B1/Cdk1, mutation of residues in the binding domain is expected to reduce this potency. To test this, S-phase cells expressing wt and mutant forms of Cdc25A were monitored for cyclin B1/Cdk1-associated histone H1 kinase activity. As seen in Fig. 4D, the binding domain mutants of Cdc25A exhibited reduced capacities to activate cyclin B1/Cdk1 in vivo. To verify that the binding domain mutants retained phosphatase activity, their ability to dephosphorylate the artificial substrate mFP in vitro was tested (49). As seen in Fig. 7E, mutation of the binding domain did not affect the intrinsic activity of Cdc25A toward mFP.

Interactions between Cdc25A and 14-3-3 proteins are cell cycle regulated. These results suggest that phosphorylation of Cdc25A on T507 and subsequent 14-3-3 binding prevent Cdc25A from binding to cyclin B1/Cdk1. This model predicts that Cdc25A should be phosphorylated on T507 and bound to 14-3-3 proteins until cells approach mitosis, at which point loss of 14-3-3 binding would promote activation of the Cdk1 kinase.

FIG. 5. 14-3-3 binding mutants induce histone H3 phosphorylation in S-phase cells. S-phase HeLa cells expressing GFP and various forms of Myc-Cdc25A (same cells as for Fig. 4) were costained for DNA content and histone H3 phosphorylation and analyzed by flow cytometry (50). Percentages of mitotic cells are indicated.

FIG. 6. Threonine 507 negatively regulates phosphatase activity of Cdc25A. wt and mutant forms of Cdc25A were purified as GST fusion proteins from bacteria (A) or as Myc fusion proteins from HeLa cells (B). Phosphatase assays were carried out in the presence of Cdc25A and purified cyclin B1/Cdk1 containing Cdk1 phosphorylated on both T14 and Y15. Phosphatase reactions were terminated and histone H1 kinase assays were performed to measure the activation of cyclin B1/Cdk1. 32P incorporation into histone H1 was determined by scintillation counting, Cdc25A precipitates were immunoblotted and quantified by use of Myc antibodies, ECF reagents, and the Storm 860 imaging system (Amersham). Histone H1 kinase activities were normalized for levels of Cdc25A in each reaction. Values obtained for wt Cdc25A were set at 100, and the mutant values are shown relative to this. Standard errors of the means (n ≥ 3) are shown as error bars along the y axis.
To test this, phospho-specific antibodies were used to examine the phosphorylation of Cdc25A on S178 and T507 throughout the cell cycle. Because of its low abundance and short half-life, we were unable to monitor the binding of endogenous Cdc25A to 14-3-3 proteins in vivo. Therefore, cells at various stages of the cell cycle were infected with recombinant adenovirus that inducibly expresses Cdc25A, and phosphorylation of S178 and T507 was monitored using phospho-specific antibodies (particularly pT507) was observed to decrease (Fig. 8C, lanes 4 and 5).

**DISCUSSION**

In this study, a new function for the Chk1 protein kinase in regulating mitotic entry is proposed (Fig. 9). We demonstrate that Chk1 phosphorylates Cdc25A at S178 and T507 in vitro and that phosphorylation of these residues mediates binding of 14-3-3 protein to Cdc25A in vivo. Because phosphorylation of Cdc25A in vivo is absolutely dependent on Chk1 (57) and because Chk1 phosphorylates Cdc25A at S178 and T507 in vivo, we conclude that Chk1-mediated phosphorylation of Cdc25A is an important factor in the regulation of mitotic entry. The results presented here provide new insights into the mechanisms by which Chk1 regulates cell cycle progression and may have implications for understanding the role of Chk1 in cancer progression and drug resistance.
vitro (Fig. 2B), we infer that Chk1 regulates S178 and T507 phosphorylation in vivo. This conclusion is supported by the finding that phosphorylation of T507 and, to a lesser extent, S178 was impaired in Chk1-deficient cells (Fig. 2C). Thus, Chk1 negatively regulates entry into mitosis by preventing functional interactions between Cdc25A and the mitotic inducer Cdk1. Sorenson et al. (46) reported that both Chk1 and Chk2 phosphorylate Cdc25A to promote its turnover. Here we show that Chk1, but not Chk2, phosphorylates Cdc25A at T507 to prevent cyclin B1/Cdk1 binding. Thus, this study uncovers a unique role for Chk1 in the negative regulation of Cdc25A.

In general, the binding of 14-3-3 proteins to their targets is mediated by the phosphorylation of the target protein at one of two 14-3-3-binding consensus motifs. These motifs include the RSXpSXP (mode 1) and RX(Y/F)XpSXP (mode 2) sequences, where pS denotes either phosphoserine or phosphothreonine (33, 54). Given that each monomer of the 14-3-3 dimer can simultaneously bind distinct phosphoepitopes on a single protein (35), it is possible that a single 14-3-3 dimer simultaneously binds to pS178 and pT507 on a single Cdc25A molecule. The sequences surrounding and inclusive of S178 (RQNpSAP) fit nicely with the mode 1 consensus, whereas sequences inclusive of and surrounding T507 (TKSRpTWA) do not fit either consensus very well. Thus, it is predicted that S178 is a higher-affinity 14-3-3 binding site and could serve a gatekeeper function, thereby increasing the affinity of 14-3-3 binding to the C-terminal cyclin B1 binding domain (BD) of Cdc25A and cyclin B1/Cdk1 throughout interphase. These regulatory pathways prevent cells from entering into mitosis at inappropriate times during the cell cycle and following checkpoint activation. Solid arrows originating from Chk1 indicate phosphorylation sites that mediate 14-3-3 binding, whereas hatched lines represent sites that mediate Cdc25A turnover. S178 is the primary 14-3-3 binding site and S75 is the primary site regulating Cdc25A turnover, as indicated by thicker arrows.

FIG. 8. Phosphorylation of Cdc25A at S178 and T507 is cell cycle regulated. HeLa cells expressing Myc-Cdc25A were synchronized at the G1/S border by a double thymidine block protocol. Cells at the G1/S border were collected prior to release from the block, and S- and G2/M-phase cells were harvested at 3 and 7 h after release, respectively. Mitotic cells were obtained by incubation in nocodazole for 10 h after infection and release. Some cells were harvested and analyzed by FACs to determine DNA content (A). The remaining cells were lysed and incubated with anti-c-Myc-agarose. Precipitates were resolved by SDS-PAGE and incubated with phospho-specific antibodies followed by antibodies specific for the Myc epitope to monitor Cdc25A levels (B and C).

FIG. 9. Regulation of Cdc25A by Chk1. Chk1 phosphorylates Cdc25A on several N-terminal serines to promote its ubiquitin-mediated proteolysis (11, 16, 20, 46, 57). Chk1 also phosphorylates Cdc25A on S178 and T507 to facilitate 14-3-3 binding. 14-3-3 binding to the C-terminal cyclin B1 binding domain (BD) of Cdc25A blocks functional interactions between Cdc25A and cyclin B1/Cdk1 throughout interphase. These regulatory pathways prevent cells from entering into mitosis at inappropriate times during the cell cycle and following checkpoint activation. Solid arrows originating from Chk1 indicate phosphorylation sites that mediate 14-3-3 binding, whereas hatched lines represent sites that mediate Cdc25A turnover. S178 is the primary 14-3-3 binding site and S75 is the primary site regulating Cdc25A turnover, as indicated by thicker arrows.
G2/M transition. This suggests that the cyclin B1/Cdk1 binding site is masked throughout much of interphase. Substitution of alanine for T507 prevented phosphorylation of Cdc25A on T507 and subsequent 14-3-3 binding at the C terminus of Cdc25A. This, in turn, is predicted to expose the cyclin B1 binding site, allowing inappropriate interactions between Cdc25A and cyclin B1/Cdk1 during S phase. This model is consistent with the observation that the single T507A and double S178A/T507A mutants were more effective in activating cyclin B1/Cdk1 both in vivo and in vitro and in promoting premature chromosome condensation and phospho-histone H3 staining during S phase.

It was recently reported that phosphorylation of S178 together with phosphorylation of serines 123, 278, and 292 regulates the turnover of Cdc25A both during interphase and in response to IR (46). It is unclear how phosphorylation of S178 regulates the turnover of Cdc25A, given that S178 phosphorylation facilitates the binding of 14-3-3 proteins to Cdc25A. It may be that S178 needed to be mutated to block 14-3-3 binding in order to observe the effects of subsequent mutations of S123, S278, and S292 on Cdc25A stability. 14-3-3 binding regulates several important mitotic regulators. 14-3-3 binding impairs the ability of Cdc25A to interact with cyclin B1/Cdk1 (this study), 14-3-3 binding to Cdc25B and Cdc25C regulates their intracellular trafficking (9, 10, 18, 19, 27, 37, 55, 56), and 14-3-3 regulates the enzymatic activity of Wee1 (28, 42). Finally, 14-3-3 prevents the nuclear accumulation of cyclin B1/Cdk1 following DNA damage (7). Thus, 14-3-3 binding to mitotic regulators is a commonly employed mechanism used by cells to regulate progression through an unperturbed cell cycle as well as following checkpoint activation.

Maintenance of the Chk1/Cdc25A pathway is essential for cells to progress normally through an unperturbed cell division cycle and for cells to arrest in response to checkpoint activation. Importantly, failure to regulate Cdc25A protein levels causes bypass of the IR-induced DNA damage checkpoint and the DNA replication checkpoint, resulting in decreased cell survival (2, 11, 29, 31, 57). Thus, drugs that induce accumulation and/or inappropriate activation of Cdc25A are expected to be potent checkpoint abrogators and may prove useful in combination therapies for treating human cancers. Specific Chk1 inhibitors may be particularly useful in this regard, as they would not only lead to Cdc25A accumulation but also to activation of cyclin B1/Cdk1 in S phase to promote mitotic catastrophe.

ACKNOWLEDGMENTS

We thank D. Morgan for recombinant adenovirus encoding rTA. We thank S. Meck for assistance with the Far Western blots, C. Nichols for the Cosmo cells, and members of the laboratory for comments on the manuscript. We thank C. Lovly for help in preparing the figures.

This work was supported by a grant from the National Institutes of Health. M.-S.C. was an Associate and H.P.-W. is an Investigator of the Howard Hughes Medical Institute.

REFERENCES