E2F-Rb Complexes Assemble and Inhibit cdc25A Transcription in Cervical Carcinoma Cells following Repression of Human Papillomavirus Oncogene Expression

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Expression of the bovine papillomavirus E2 protein in cervical carcinoma cells represses expression of integrated human papillomavirus (HPV) E6/E7 oncogenes, followed by repression of the cdc25A gene and other cellular genes required for cell cycle progression, resulting in dramatic growth arrest. To explore the mechanism of repression of cell cycle genes in cervical carcinoma cells following E6/E7 repression, we analyzed regulation of the cdc25A promoter, which contains two consensus E2F binding sites and a consensus E2 binding site. The wild-type E2 protein inhibited expression of a luciferase gene linked to the cdc25A promoter in HT-3 cervical carcinoma cells. Mutation of the distal E2F binding site in the cdc25A promoter abolished E2-induced repression, whereas mutation of the proximal E2F site or the E2 site had no effect. None of these mutations affected the activity of the promoter in the absence of E2 expression. Expression of the E2 protein also led to posttranscriptional increase in the level of E2F4, p105^{Rb}, and p130 and induced the formation of nuclear E2F4-p130 and E2F4-p105^{Rb} complexes. This resulted in marked rearrangement of the protein complexes that formed at the distal E2F site in the cdc25A promoter, including the replacement of free E2F complexes with E2F4-p105^{Rb} complexes. These experiments indicated that repression of E2F-responsive promoters following HPV E6/E7 repression was mediated by activation of the Rb tumor suppressor pathway and the assembly of repressing E2F4-Rb DNA binding complexes. Importantly, these experiments revealed that HPV-induced alterations in E2F transcription complexes that occur during cervical carcinogenesis are reversed by repression of HPV E6/E7 expression.

Cells have evolved complex regulatory mechanisms to ensure orderly progression through the cell cycle. One of the major regulatory systems entails the interactions between members of the retinoblastoma susceptibility (Rb) protein family and E2F transcription factors. p105^{Rb} and other members of the Rb family, p107 and p130, form complexes with various members of the E2F family and regulate their activity (15, 43). E2F transcription factors exist as stable heterodimers with DP subunits. During the G₁ and G₀ phases of the cell cycle, complexes consisting of E2F-DP heterodimers and hypophosphorylated Rb proteins actively repress promoters that contain E2F binding sites (21, 25, 27, 33, 35, 40, 42, 58, 61). Many of the genes repressed in this fashion encode proteins that are required for entry into and transit through S phase, and E2F4-p105^{Rb} and E2F4-p130 complexes are particularly active in transcriptional repression (9, 39, 53, 54, 57). In addition, complex formation with Rb family members protects E2F proteins from degradation by the ubiquitin-proteasome pathway and promotes the localization of E2F4 to the nucleus (22, 26, 37, 38). In contrast, phosphorylation of Rb family members by cyclin-dependent kinases during cell cycle progression disrupts Rb-containing E2F complexes and releases free E2F-DP heterodimers that may then act as transcriptional activators at promoters containing E2F binding sites (15, 43). The impor-

tance of E2F-Rb complexes in regulating cell growth is underscored by the finding that diverse DNA tumor viruses encode proteins that disrupt these complexes, leading to uncontrolled cell growth (44).

The genes encoding p53 and p105^{Rb} are frequently mutant in a variety of human cancers. In contrast, cervical carcinomas and carcinoma-derived cell lines often contain wild-type tumor suppressor genes (7, 46). These cancers almost invariably harbor high-risk human papillomavirus (HPV) genomes and express the viral oncogenes E6 and E7 (56). The high-risk HPV E6 and E7 proteins bind to p53 and p105^{Rb} (and other Rb members), respectively, and neutralize their growth-inhibitory function. The E6 protein targets p53 for ubiquitin-mediated proteolysis (47). Similarly, the E7 protein targets Rb family members for ubiquitin-mediated proteolysis, resulting in decreased Rb levels in cells expressing the viral protein (1, 3, 34). In addition, the E7 protein sequesters Rb proteins so that free E2F is released (4). Cells expressing high-risk E6 and E7 proteins display impaired checkpoint control following DNA damage and exhibit elevated rates of mutagenesis (10, 11, 23, 24, 50, 59). Thus, even though cervical carcinoma cells often maintain wild-type p53 and p105^{Rb} genes, tumor suppressor activity is largely eliminated, implying that HPV-infected cervical epithelial cells are subjected to continuing genetic insults which may ultimately result in irreversible loss of growth control.

In contrast to the HPV E6 and E7 genes, the HPV E2 gene is frequently disrupted in cervical carcinomas (56), presumably reflecting the ability of the papillomavirus E2 proteins to bind directly to the HPV early promoter and repress transcription of the E6 and E7 genes (2). Ectopic expression of HPV or

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bovine papillomavirus (BPV) E2 proteins in cervical carcinoma cell lines such as HeLa or HT-3 cells, which contain HPV type 18 (HPV18) or HPV30 DNA, respectively, results in the specific and rapid repression of the endogenous HPV E6 and E7 genes and in significant growth inhibition, with the inhibited cells accumulating with G_0/G_1 DNA content (12, 13, 29, 30, 41). Several lines of indirect evidence indicate that E2-induced growth inhibition is mediated by repression of E6/E7 expression (20, 41), and it has recently been shown that constitutive expression of the HPV16 E6/E7 proteins can block the growth-inhibitory effect of the E2 protein (17; Goodwin and DiMaio, submitted). Expression of the E2 protein and repression of HPV E6 and E7 expression results in the subsequent accumulation of hypophosphorylated p105^{Rb} and repression of the E2F1, cyclin A, and *cdc25A* genes (29, 41; Goodwin and DiMaio, submitted). *cdc25A* encodes a protein tyrosine phosphatase that can remove inhibitory phosphates from cyclin-dependent kinases and is required for cell cycle progression in cervical carcinoma cells (reviewed in reference 14). Taken together, these results suggest that growth-regulatory pathways in the cervical cancer cells are largely intact but dormant until they are mobilized by the E2 protein. Thus, the E2 protein can be used as a reagent to repress E6/E7 expression, reactivate tumor suppressor pathways, and explore the consequences on cell physiology. Unlike experiments involving introduction of foreign cellular genes, this approach induces expression of endogenous tumor suppressor proteins, an experimental design less prone to artifacts due to protein overexpression or interactions between heterologous proteins.

Here, we analyzed the regulation of the human *cdc25A* promoter in cervical carcinoma cells in response to the E2 protein and repression of E6/E7 expression. We show that the E2 protein represses *cdc25A* transcription by inducing the assembly of functional E2F-Rb transcriptional repressor complexes that bind to the *cdc25A* promoter. Thus, the alterations in the composition and function of E2F-Rb transcription complexes that occur during cervical carcinogenesis are reversible.

MATERIALS AND METHODS

DNAs. The *XhoI*-to-*XbaI* fragment containing the human *cdc25A* promoter was isolated from genomic clone pBSK-*cdc25A* 12E (18) and inserted into *XhoI*-plus-*NheI*-digested pGL3 basic (Promega) to generate pGL3b-*cdc25A*-XX. E2 site mutations were constructed in pGL3b-*cdc25A*-BX, which contains the *Bam*HI-to-*XhoI* fragment of the human *cdc25A* promoter, by using a QuikChange mutagenesis kit (Stratagene). The luciferase reporter containing the wild-type *SacI* promoter fragment and fragments containing mutations in the E2F sites were described previously (55).

Cells and virus stocks. HT-3 cells were maintained in McCoy's 5A medium containing 15% fetal bovine serum. BPV1-simian virus 40 (SV40) recombinant virus stocks were prepared and titered as described previously (41). To generate HT-3 cells containing a stably integrated reporter plasmid, 5×10^5 cells were plated in a 60-mm-diameter tissue culture dish. When the cells were 80% confluent, 12 μ l of Lipofectamine was mixed with 5 μ g of pGL3b-*cdc25A*-XX and 0.5 μ g of pBabe-puro in 3 ml of Opti-MEM medium, and the transfection mixture was incubated with the cells for 6 h (20). At 72 h after transfection, the cells were passaged in 1:10 into medium containing 1 μ g of puromycin per ml. Individual puromycin-resistant colonies were isolated, expanded into cell lines, and tested for luciferase expression in the absence of E2 expression. The cell line displaying the highest basal level of luciferase activity was used for further experiments.

Infection, transfection, and luciferase assays. HT-3 cells were plated at a density of 10^5 cells/well in a 24-well tissue culture plate and grown overnight. The cells were then infected with recombinant virus in 200 μ l of Dulbecco's modified Eagle's medium containing 2% fetal bovine serum for 5 h with tilting at 37°C. The cells were washed twice with phosphate-buffered saline (PBS) and transfected with 1 μ g of firefly luciferase reporter plasmids by using 2.5 μ l of Lipofectamine as described above. Cells were lysed in 200 μ l of cell culture lysis reagent 48 h after infection, and luciferase activity was measured by using the Promega luciferase assay system. Each experiment was performed in duplicate or triplicate, and the results shown in each figure are the average for a representative experiment, with the error bars showing standard deviation.

Northern blot analysis. Total RNA was prepared from HT-3 cells with Trizol (Life Technologies) 48 h after mock infection or infection at a multiplicity infection (MOI) of 20, subjected to formaldehyde-agarose gel electrophoresis, and transferred to Nytran supercharge (Schleicher and Schuell). E2F cDNAs labeled with [α -³²P]dATP by random priming were used to probe replicate filters.

Preparation of cell extracts. (i) **Nuclear extracts.** HT-3 cells were plated at 2.2×10^6 cells per 10-cm-diameter culture dish, grown overnight, and then mock infected or infected with virus at an MOI of 20. At 24, 48, or 60 h after infection, cells were washed twice with PBS and then lysed in 800 μ l of buffer A (10 mM HEPES [pH 7.9], 10 mM KCl, 0.1 mM EDTA, 0.1 mM EGTA, 1 mM dithiothreitol [DTT], 0.5 mM phenylmethylsulfonyl fluoride) for 15 min on ice. After addition of 50 μ l of 10% NP-40 (Sigma), vigorous vortex mixing, and brief microcentrifugation, the nuclear pellet was resuspended in 100 μ l of buffer C (20 mM HEPES [pH 7.9], 400 mM NaCl, 1 mM EDTA, 1 mM EGTA, 1 mM DTT, 1 mM phenylmethylsulfonyl fluoride and incubated on ice for 20 min. After centrifugation in a microcentrifuge at maximum speed for 10 min, the supernatant was used immediately or stored at -70°C.

(ii) **Whole-cell extracts.** At 48 h after infection, cells were washed twice with cold PBS and scraped in 10 ml of cold PBS. The cells were centrifuged and suspended in lysis buffer (20 mM HEPES [pH 7.6], 420 mM NaCl, 1.5 mM MgCl₂, 0.2 mM EDTA, 25% glycerol) supplemented with proteinase inhibitors. Extracts were stored at -70°C.

Proteasome inhibitor studies. HT-3 cells were plated at a density of 2.2×10^6 cells/100-mm-diameter tissue culture dish. After overnight growth, the cells were incubated for 12 h with LLnL (50 μ g/ml; Sigma) or MG132 (20 μ g/ml; Calbiochem) in McCoy's 5A medium containing 15% fetal bovine serum. The cells were then washed twice with cold PBS, and whole-cell extracts were prepared by lysis in 0.1% NP-40 lysis buffer (250 mM NaCl, 0.1% NP-40, 50 mM Tris-Cl, 5 mM EDTA) containing protease inhibitors. Extracted protein (2 mg) was immunoprecipitated and immunoblotted with the appropriate monoclonal antibodies. As controls, cells were also harvested without inhibitor treatment 48 h after infection with the E2 virus or after mock infection.

Western blot and immunoprecipitation analyses. Western blots were performed with whole-cell extracts, unless specified differently in a figure legend. Extracted protein (25 μ g) was electrophoresed in a sodium dodecyl sulfate-11% polyacrylamide gel for E2F1 and E2F4 blots. The separated proteins were transferred to nitrocellulose membrane and blotted with antibodies (Upstate Biotechnology, catalogue no. 05-379 [E2F1] or 05-312 [E2F4]) in PBS containing 3% nonfat milk.

Immunoprecipitation was performed by adding 2 μ g of E2F4 antibody (sc-866; Santa Cruz Biotechnology, Inc.) or nonimmune rabbit serum to 200 μ g of total protein. After incubation at 4°C overnight, 50 μ l of protein A/G PLUS-Agarose (Santa Cruz) was added, incubation was continued for another 2 h, and then the mixture was washed four times with lysis buffer. The antibodies used to probe Western blots of Rb family members were 140010 (PharMingen) for p105^{Rb}, sc-317 (Santa Cruz) for p130, and sc-318 (Santa Cruz) for p107.

Mobility shift assays. Mobility shift assays were performed as described by Hurford et al. (29) with a double-stranded oligonucleotide probe end labeled with polynucleotide kinase and [γ -³²P]ATP (top strand, 5'-GTGGATTCCGTTTGGCGCAACTAGGAAAG-3'; nucleotides [nt] -72 to -43 of the human *cdc25A* promoter containing E2F binding site 1). Fresh nuclear extracts containing 20 μ g of extracted protein were incubated with 0.5 to 1 ng of end-labeled probe for 15 min at room temperature in 15 μ l of reaction buffer containing 25 μ g of sonicated salmon sperm DNA per ml, 20 mM HEPES (pH 7.5), 4% Ficoll 400-DL, 2.5 mM MgCl₂, 40 mM KCl, 0.1 mM EGTA, 2 mM spermine, 0.5 mM DTT, and 0.5 μ g of acetylated bovine serum albumin (Gibco-BRL) per μ l. The samples were loaded onto a 4% native polyacrylamide gel prerun at 100 V for 30 min in 0.25 $\times$ Tris-borate-EDTA buffer at 4°C and then electrophoresed at 180 V for 3 h. The gel was fixed with 10% acetic acid for 10 min, dried, and exposed. Unlabeled double-stranded oligonucleotides containing the wild-type or mutant E2F site 1 or the wild-type E2F site 2 (top strand, 5'-GCCGCTATTACCGCGAAAGCGCGCTGGC-3') were used as competitors. Supershifts were performed by addition of the appropriate antibodies (0.8 μ g of anti-human E2F1 Powerclonal [Upstate Biotechnology] for E2F1 supershift, sc-999 [Santa Cruz] for E2F5, and 140010 [PharMingen] for p105^{Rb}; 4 μ l of WuF-10 monoclonal antibody [obtained from F. Dick] for E2F4) to the mixture of protein and probe and incubation for another 20 min prior to electrophoresis.

RESULTS

Analysis of *cdc25A* promoter activity by using an integrated reporter construct. We previously showed that acute expression of the BPV E2 protein caused a dramatic reduction in HPV E6/E7 expression in HeLa and HT-3 cervical carcinoma cells, followed by repression of endogenous *cdc25A* mRNA and protein (30, 41; Goodwin and DiMaio, submitted). Since HT-3 cells contain transactivation-defective p53 (41), we focused on these cells to explore regulation of the *cdc25A* gene

FIG. 1. (A) Map of the human *cdc25A* promoter. The top line shows the positions of restriction endonuclease cleavage sites and consensus binding sites for the E2 protein and E2F. Numbers indicate the number of nucleotides from the transcription start site. Lines at the bottom part show the promoter fragments used in this study. (B) Sequences of the wild-type and mutant transcription factor binding sites in the *cdc25A* promoter. The invariant nucleotides that constitute the consensus E2 recognition site are underlined. Mutant nucleotides are shown in lowercase.

in the absence of a p53 response. To determine whether the *cis*-acting elements responsible for *cdc25A* repression resided in the 5' flanking region of the gene, we carried out experiments that utilized a reporter gene linked to the human *cdc25A* promoter. A 1,676-bp *XbaI*-to-*XhoI* fragment of the promoter extending from nt -1553 to +123 relative to the transcription start site was cloned upstream of the firefly luciferase gene (Fig. 1A). Initiation of *cdc25A* translation occurs downstream of the *SacI* site at nt +418. This reporter construct was stably introduced into HT-3 cells by selection for a co-transfected puromycin resistance gene.

HT-3 cells containing the integrated *cdc25A* promoter-luciferase gene were infected at various MOIs with a BPV-SV40 recombinant virus that expresses a wild-type BPV E2 protein. At 48 h after infection, cells were harvested and extracts were assayed for luciferase activity. As shown in Fig. 2A, virus infection caused a dose-dependent reduction in luciferase activity. At high MOI, luciferase activity was reduced approximately fivefold. In contrast, infection with a virus expressing an inactive E2 truncation mutant did not repress the *cdc25A* promoter. These experiments provided evidence that repression of the *cdc25A* gene was at the transcriptional level and demonstrated that the 5' flanking region of the *cdc25A* gene contained elements that responded to the E2 protein.

Identification of elements of the *cdc25A* promoter that mediate repression. To carry out a mutational analysis of the *cdc25A* promoter, cells were infected at high MOI with recombinant viruses expressing wild-type or mutant E2 proteins, incubated for 5 to 6 h, and then transfected with various luciferase-based reporter plasmids. Extracts harvested 48 h after infection were assayed for luciferase activity. Although the wild-type E2 protein did not repress the luciferase gene driven by the SV40 early promoter, it caused an approximately fivefold repression of the luciferase gene driven by the *XbaI*-*XhoI* fragment containing the wild-type *cdc25A* promoter (Fig. 2B). In contrast, the *cdc25A* promoter was not repressed by infection with viruses expressing a truncated E2 mutant or a DNA binding-defective E2 point mutant, neither of which repressed the endogenous *cdc25A* gene (20, 41).

The segment of the *cdc25A* promoter conferring E2 responsiveness contained a single consensus binding site for the E2 protein itself located at nt -441 to -430 and two consensus E2F binding sites near the transcription start site (Fig. 1A). To test whether these elements were responsible for E2-mediated repression of the *cdc25A* reporter, we constructed mutations at these sites, transiently transfected each mutant construct into HT-3 cells, infected the cells 6 h later with viruses expressing the E2 protein, and measured luciferase activity after an additional 42 h. The mutations tested are shown in Fig. 1B. To

destroy the E2 binding site, two point mutations were introduced into the consensus sequence absolutely required for E2 DNA binding. These mutations were introduced into a 576-bp *BamHI*-to-*XhoI* promoter fragment (nt -453 to +123). The wild-type promoter fragment was repressed approximately fourfold by the E2 protein, indicating that elements responsible for E2-induced repression resided in this fragment (Fig. 3A). The mutations in the E2 site had no significant effect on the basal level of *cdc25A* promoter activity, and they did not affect E2-mediated repression (Fig. 3A). Thus, an intact E2 binding site was not required for E2-mediated repression of the human *cdc25A* promoter.

We next tested the effect of mutations in the two E2F consensus sites in the *cdc25A* promoter. We designate the site at nt -3 to +5, more proximal to the transcription start site, as site 2 and the distal site at nt -62 to -55 as site 1. Mutations known to prevent E2F binding to site 1 or site 2 were introduced into a 1,173-bp *SacI* fragment (nt -755 to +418) containing the *cdc25A* promoter (55). As shown in Fig. 3B, the wild-type *SacI* promoter fragment was efficiently repressed by the wild-type E2 protein. The level of luciferase expression in the absence of the E2 protein was not affected by mutation of either E2F site, and mutation of E2F binding site 2 did not interfere with E2-mediated repression. Strikingly, however, mutations in E2F site 1 abolished E2-mediated repression of the *cdc25A* promoter. Similar results were obtained in four independent transfection experiments. Thus, E2-mediated repression of the *cdc25A* promoter did not appear to be a direct effect of the E2 protein binding to the promoter but rather required an intact E2F site located approximately 60 bp upstream from the transcription start site. Mutations at two additional elements between the two E2F sites, a CHR site and an Sp1 site, did not affect E2-mediated repression (data not shown).

Expression of E2F and Rb family members in response to the E2 protein. The simplest explanation for the results presented above is that the E2 protein induced the synthesis of a protein that repressed promoter activity and that this protein must bind to E2F site 1 to exert this repressing effect. E2F family members, when bound to Rb family members, can repress transcription from promoters containing E2F sites, suggesting that E2F-Rb complexes might be this putative repressor. We previously showed that the E2 protein caused a dramatic increase in the level of hypophosphorylated p105^{Rb} and a decrease in the level of E2F1 in HeLa and HT-3 cells (29, 41). Here, we used Western blotting to assess the levels of all three Rb proteins, p105^{Rb}, p107, and p130, 2 days after introduction of the E2 gene. As shown in Figure 4A (right), we confirmed the induction of the full-length hypophosphorylated

FIG. 2. E2-mediated repression of the *cdc25A* promoter. (A) HT-3 cells harboring a stably integrated *cdc25A XbaI-to-XhoI* promoter fragment linked to the luciferase gene were infected at the indicated MOI with recombinant viruses expressing the wild-type or a nonsense mutant (E2 Am) E2 protein. Luciferase activity was measured on cell extracts prepared 48 h after infection. (B) Cells were mock infected (–) or infected with viruses expressing the wild-type E2 protein (wt), the DNA binding-defective mutant K339M (339M), or the E2 nonsense mutant (Am) at an MOI of 20. After 5 to 6 h, the cells were transfected with the luciferase gene linked to the SV40 early promoter or to the wild-type *XbaI-to-XhoI cdc25A* promoter fragment; after an additional 2 days, cells were harvested and luciferase activity was measured.

form of p105^{Rb}. (HT-3 cells also express a deleted version of p105^{Rb}, whose expression is not affected by E2 expression [41]). The level of p130 also markedly increased in response to E2 expression, whereas p107 expression was unchanged (Fig. 4A, right). Because of the well-known repressing activity of E2F4 when it is associated with Rb family members, we also assessed the expression of E2F4. There was a dramatic increase in the amount of E2F4 in HT-3 nuclear extracts (and in whole-cell extracts [see Fig. 5]) in response to expression of the E2 protein, whereas in confirmation of earlier results, E2F1 expression was inhibited by the E2 protein (Fig. 4A, right).

We used Northern blotting to explore the mechanism by which the E2 protein affected the concentration of Rb and E2F family members. As shown in Fig. 4A (left), E2 expression did not cause an increase in the levels of the mRNA encoding

FIG. 3. Analysis of the *cdc25A* promoter containing mutations in transcription factor binding sites. (A) E2 binding site. Cells were mock-infected (–) or infected with a virus expressing the wild-type (wt) or nonsense mutant (Am) E2 protein, as indicated. After 5 to 6 h, the cells were transfected with the luciferase gene linked to the wild-type *BamHI-XhoI* fragment of the *cdc25A* promoter or the fragment containing two mutations in the consensus E2 binding site, and luciferase activity was determined. (B) E2F sites. Cells were mock infected (–) or infected with a virus expressing the wild-type E2 protein (wt). After 5 to 6 h, cells were transfected with the luciferase gene linked to the wild-type *SacI* fragment of the *cdc25A* promoter or fragments containing mutations in either E2F site 1 or E2F site 2, and luciferase activity was determined.

p105^{Rb}, p130, or E2F4. Therefore, the induction of these proteins in response to E2 expression did not reflect increased transcription or mRNA stability. In contrast, E2F1 mRNA was reduced, as reported earlier. The levels of E2F3 and E2F5 mRNA did not change in response to E2 expression (data not shown).

The results presented above demonstrated that the E2 protein caused posttranscriptional induction of p105^{Rb}, p130, and E2F4. The relatively low concentrations of endogenous E2F4 and p105^{Rb} in proliferating HT-3 cells prevented us from directly measuring changes in the half-life of these proteins in response to E2 expression. As an alternate approach, we tested whether E2F4 and p105^{Rb} levels were controlled by proteasome-mediated proteolysis in cervical carcinoma cells, as they are in other cell types (1, 3, 34). Cells were incubated with the peptide aldehyde LLnL or MG132, specific inhibitors of the

FIG. 4. (A) Expression of E2F and Rb family members. (Right) Nuclear (top two panels) and whole-cell (bottom three panels) extracts were prepared 48 h after mock infection (–) or infection with a virus expressing the wild-type E2 protein (E2). After gel electrophoresis and transfer, filters were probed with antibody recognizing p105^{Rb}, p107, p130, E2F4, or E2F1, as indicated. ΔRb is the deleted form of p105^{Rb} expressed in HT-3 cells. (Left) RNA was isolated 48 h after mock infection (–) or after infection with a virus expressing the wild-type E2 protein (E2). After gel electrophoresis and transfer, filters were hybridized to the indicated radiolabeled cDNA probes. (B) Complex formation between E2F4 and Rb family members. Nuclear extracts from E2-infected and mock-infected cells were immunoprecipitated (IP) with nonimmune rabbit serum (NRS) or anti-E2F4 (αE2F4) rabbit antiserum, electrophoresed, and transferred. The filter was then probed sequentially with antibodies recognizing p105^{Rb} and p130, as indicated.

26S proteasome, or dimethyl sulfoxide (DMSO) alone. In parallel, cells were mock-infected or infected with the E2 virus. We then performed immunoprecipitation and Western blotting on equal amounts of total cell protein to examine levels of p105^{Rb} and E2F4. This analysis was performed with whole-cell lysates, to eliminate relocalization to the nucleus as a cause of apparent differences in expression levels. As shown in Fig. 5A, in mock-infected cells, most of the E2F4 migrated as a single band upon gel electrophoresis. Following LLnL treatment or expression of the E2 protein, the amount of E2F4 in this band increased, and multiple additional E2F4 bands with different electrophoretic mobilities were detected. Similar results were obtained when cells were treated with MG132 (data not shown). The more complex pattern of E2F4 expression in whole cells compared to nuclear extracts (Fig. 4A, right) presumably reflects the presence of additional modified E2F4 species in nonnuclear locations. Similarly, LLnL or MG132 treatment of uninfected cells or expression of the E2 protein resulted in increased levels of full-length p105^{Rb} but not the deleted form (Fig. 5B). We conclude that E2F4 and p105^{Rb} are subject to rapid proteasome-mediated degradation in proliferating HT-3 cells. Furthermore, these results suggest that the E2 protein may directly or indirectly protect these cell cycle-regulatory proteins from this fate, contributing to the increased concentration that is observed. However, these experiments do not rule out the possibility that the E2 protein exerts additional effects on the expression of p105^{Rb} or E2F4.

Because complexes containing E2F4 and Rb family members can repress transcription, we determined whether E2 expression induced the formation of such complexes. We carried out immunoprecipitation with a rabbit polyclonal anti-E2F4 antibody and immunoblotted the resulting immunoprecipitates with antibodies that recognize p105^{Rb} or p130. As shown in Fig. 4B, the anti-E2F4 antibody immunoprecipitated little, if any, p130 or p105^{Rb} from nuclear extracts of uninfected cells. In contrast, E2 expression caused a dramatic increase in the amount of p105^{Rb} and p130 coimmunoprecipitated by the anti-E2F4 antibody. Similar results were obtained by immunoprecipitation with a monoclonal antibody that recognizes E2F4

FIG. 5. Effect of proteasome inhibitors on E2F4 and p105^{Rb} levels. Cells were mock infected (M), infected with a virus expressing the wild-type E2 protein (E2), treated with LLnL (L) or MG132 (MG) in DMSO, treated with DMSO alone (D), or incubated in normal medium (N), as indicated. NP-40 whole-cell lysates were prepared, and E2F4 (A) or p105^{Rb} (B) was immunoprecipitated from equal amounts of extracted protein, electrophoresed, transferred to filters, and detected by probing the filters with specific antibodies.

(data not shown), and nonimmune rabbit antiserum did not immunoprecipitate the Rb family members (Fig. 4B). E2 expression did not affect the level of p107 in complex with E2F4 (data not shown). Therefore, expression of the E2 protein and repression of HPV30 E6 and E7 resulted in elevated levels of E2F4-p105^{Rb} and E2F4-p130 complexes in the nuclei of HT-3 cells.

Oligonucleotide mobility shift analysis. We carried out oligonucleotide mobility shift experiments to examine the protein complexes capable of forming on E2F site 1, which mediates E2 repression of the cdc25A promoter. A 30-bp double-stranded oligonucleotide spanning this site was end labeled and incubated with nuclear extracts of uninfected HT-3 cells and of cells infected with the virus expressing the wild-type E2 protein. After electrophoresis through a nondenaturing gel, DNA-protein complexes were visualized by autoradiography. As shown in Fig. 6A, nuclear extracts from mock-infected HT-3 cells gave rise to three prominent retarded species, labeled A, B, and C. Expression of the E2 protein caused a dramatic change in the pattern of retarded bands. Band A persisted and was reproducibly more abundant following E2 expression, band B was markedly reduced in intensity, and two new major bands (D and E) appeared that comigrated with minor bands generated by the mock extracts. Band C was generated in similar amounts by both samples. To examine the specificity of these complexes, competition studies were carried out. Bands A, B, D, and E were competed by excess unlabeled oligonucleotide containing the wild-type E2F site 1 but not by an oligonucleotide containing the same mutation that abolished repression (Fig. 6A). In addition, these bands were not observed when a mutant oligonucleotide was used as a probe (data not shown). Thus, bands A, B, D, and E represent specific E2F complexes whose abundance varies in response to E2 expression. In contrast, band C was not competed by the unlabeled wild-type oligonucleotide, indicating that it was not a specific complex. Therefore, expression of the E2 protein and repression of E6/E7 expression resulted in a dramatic alteration in the protein complexes that specifically bound E2F site 1. If infection was allowed to proceed for 60 h or if it was carried out at higher MOI, band D was by far the most abundant complex formed at E2F site 1 (Fig. 6B and data not shown).

To identify the proteins present in complexes forming at E2F site 1, we performed supershift analysis with specific antibodies (Fig. 7). Band B was supershifted by the E2F1 antibody, generating band b. This is consistent with the reduction of intensity of band B in response to the E2 protein, which represses E2F1 expression. In contrast, band A generated by

FIG. 6. (A) E2F DNA binding complexes in HT-3 cells. Nuclear extracts were prepared 48 h after mock infection or after infection with a virus expressing the wild-type E2 protein, as indicated. Extracts were incubated with radiolabeled wild-type E2F site 1 oligonucleotide alone or with probe plus 100-fold excess of the unlabeled wild-type (wt) oligonucleotide or a mutant (mut) one containing the E2F site 1 mutations shown in Fig. 1B. Bound protein complexes were separated by gel electrophoresis and detected by autoradiography. The letters indicate the specific bands referred to in the text. (B) E2F DNA binding complexes at various times after infection. Nuclear extracts were prepared 24 and 60 h after mock infection or after infection with a virus expressing the wild-type E2 protein, as indicated. Extracts were incubated with radiolabeled oligonucleotide containing wild-type E2F site 1. Bound protein complexes were separated by gel electrophoresis and detected by autoradiography. The letters indicate the specific bands referred to in the text. Where indicated, supershift analysis was carried out with antibody recognizing p105^{RelB} or E2F4.

extracts of control and E2-expressing cells was supershifted by the anti-E2F4 antibody, generating band a. Band D, which was prominent only in extracts of E2-expressing cells, was efficiently supershifted by anti-p105^{Rb}, generating band d, indicating that it contains p105^{Rb}. Supershift analysis of extracts prepared 60 h after infection confirmed that band D, the only prominent complex at this time point, contained p105^{Rb} (Fig. 6B). In addition, band D was eliminated by anti-DP antibody.

further indicating that it contained an E2F family member (data not shown). Band D was partially supershifted by anti-E2F4 antibody, suggesting that this band may be a mixture of complexes that contain p105^{Rb} and various E2F family members (Fig. 6B and 7). Bands A, B, and E were not supershifted by antibodies to Rb family members, and none of the prominent bands generated by either set of extracts were supershifted by E2F5, p107, or p130 antibodies (Fig. 7 and data not shown). Although we have not identified the proteins present in complex E, its relatively rapid mobility and the supershift analysis summarized above suggest that it does not contain Rb family members. Furthermore, the disappearance of complexes A and E at later times after infection or after infection at higher MOI indicates that these complexes are not involved in maintenance of *cdc25A* repression.

We also tested the ability of E2F site 2, which is not required for repression of the *cdc25A* promoter, to compete for the protein complexes formed at site 1. Extracts prepared 60 h after infection were incubated with radiolabeled oligonucleotide containing site 1 and various amounts of unlabeled oligonucleotides containing site 1 or site 2. As shown in Fig. 8, band D was the predominant retarded species formed on site 1 at this time point, and it was efficiently competed by unlabeled site 1. Site 2 also competed for the formation of band D, but it was a much less effective competitor than site 1. We conclude that p105^{Rb}-containing complexes can bind in vitro to either E2F site 1 or site 2, but that the complex binds with higher affinity to site 1, which mediates repression, than to site 2, which does not. Taken together, the results presented in this section strongly suggest that the E2F4-p105^{Rb} complex detected by coimmunoprecipitation is likely responsible at least in part for the appearance of band D and that the binding of this complex or a related complex to E2F site 1 in the *cdc25A* promoter mediates E2-induced repression of the *cdc25A* gene.

FIG. 7. Identification of protein complexes that bind E2F site 1. Nuclear extracts were prepared as described in the legend to Fig. 6A. Extracts were incubated with wild-type radiolabeled oligonucleotide probe alone (–) or in the presence of the indicated antibody. Bound protein complexes were separated by gel electrophoresis and detected by autoradiography.

FIG. 8. Competition between E2F site 1 and E2F site 2. Nuclear extracts were prepared at 60 h after mock infection or infection with a virus expressing the wild-type E2 protein. Extracts were incubated with radiolabeled wild-type E2F site 1 oligonucleotide probe alone (–) or in the presence of 1-, 5-, 10-, or 50-fold excess of unlabeled oligonucleotide containing E2F site 1 or E2F site 2, as indicated. Bound protein complexes were separated by gel electrophoresis and detected by autoradiography.

DISCUSSION

Cell cycle regulatory components have been extensively studied in a variety of situations in which cells are induced to enter or exit the cell cycle. However, it is difficult to restore growth control in human cancer cells, because the growth-regulatory pathways in these cells are typically disrupted by mutation. In contrast, the p53 and Rb genes are frequently wild type in cervical carcinoma cells, but their action is masked by the expression of HPV oncogenes. Therefore, these cells represent a unique system to characterize endogenous growth-regulatory pathways in cancer cells, with the hope of identifying pathways that can be manipulated to restore growth control.

To explore the functional consequences of HPV E6/E7 repression on cellular transcription in cervical carcinoma cells, we analyzed the regulation of the *cdc25A* promoter following repression of E6/E7 expression in HT-3 cells. We first showed that the elements controlling the response of the *cdc25A* promoter to the E2 protein were contained in a ~500-bp DNA fragment upstream of the translation initiation site. This segment of DNA contains two E2F binding sites, as well as a consensus recognition site for the E2 protein itself. Although an intron of the human *cdc25A* gene contains an element that binds and responds to Myc and Max transcription factors (18), the fragment conferring E2 responsiveness does not include this element, demonstrating that it was not required for repression in this system. Similarly, our results established that the putative E2 binding site in the *cdc25A* promoter was not required for E2-mediated repression. Therefore, the *cdc25A* promoter, unlike the HPV early promoter, is not directly repressed by binding of the E2 protein.

Our results showed that E2-induced repression of the *cdc25A* promoter was mediated through E2F control. The activity of the *cdc25A* promoter in proliferating cells was not affected by mutating the E2F sites, ruling out the model that

the E2 protein prevented a stimulatory factor from binding to these sites. Instead, mutation of E2F site 1 eliminated E2-mediated repression of the *cdc25A* promoter, suggesting that the E2 protein induced the expression or activity of an E2F-containing factor that binds to this site and causes repression.

We characterized E2F-containing complexes in HT-3 cells to explore the basis for the E2F site 1-dependent repression of the *cdc25A* promoter. E2 expression caused marked changes in the abundance of E2F factors and Rb family members. E2F1 levels were depressed, whereas there was increased posttranscriptional accumulation of E2F4, p105^{Rb}, and p130. Several mechanisms probably contribute to these effects. In various cell types, high-risk HPV E7 induces rapid degradation of p105^{Rb} via the ubiquitin-proteasome pathway (1, 3, 34). Our results show that this pathway targets p105^{Rb} for rapid degradation in cervical carcinoma cells and suggest that this process can be reversed by repression of HPV E7 expression. In addition, it has been reported that complex formation with Rb family members protects E2F factors from rapid proteasome-mediated degradation (22, 26). The data presented here suggest that induction of endogenous Rb expression in cervical carcinoma cells can result in the stabilization of E2F4 by this mechanism. The abundance of nuclear E2F4-p105^{Rb} and E2F4-p130 complexes increased dramatically as a consequence of the elevated concentrations of the interacting species. In addition, enhanced nuclear localization of E2F4 when it is in complex with Rb family members (37, 38) may also contribute to the accumulation of these complexes in the nucleus.

The E2 protein also caused dramatic changes in the pattern of protein complexes forming at the E2F site responsible for repression of the *cdc25A* promoter. Complexes containing free E2F1 decreased following E2 expression, whereas complexes containing free E2F4 persisted and even increased in abundance, at least during the initial stages of infection. Most strikingly, the E2 protein induced the appearance of a prominent p105^{Rb}-containing complex at the E2F site required for repression. This complex, which appeared to also contain E2F4 or possibly another E2F family member, may also be present in low amounts in proliferating cells, but its abundance increased markedly following E2 expression, and at late times after infection it was the only specific complex formed at site 1 in abundance. This complex was inefficiently competed by site 2, which does not mediate repression. Therefore, we infer that this Rb-containing complex was likely to be responsible for E2-mediated repression. It has recently been shown that E2F site 1 in the *cdc25A* promoter is required for repression of the *cdc25A* gene by serum starvation or transforming growth factor β treatment (5, 31, 55), as it is in response to the E2 protein. The importance of this site for negative regulation of the *cdc25A* gene in these different situations suggests that diverse signals converge on a single common pathway to regulate *cdc25A* transcription. Transforming growth factor β and alpha interferon treatment also induces the formation of complexes between E2F4 and Rb family members; however, gel shift analysis using the E2F sites from the *cdc25A* promoter was not carried out, and so it is not known which complexes actually formed at the promoter in response to these treatments (31, 36, 52). Gel shift analysis implied that E2F-p130 complexes forming at E2F site 1 were responsible for repression of the human *cdc25A* promoter in serum-starved mouse NIH 3T3 cells (5). In contrast to our results, p105^{Rb} complexes were not observed in this heterologous system.

Our results suggest that E2-mediated repression of cell cycle genes in HT-3 cells involves the following sequence of events. By analogy to the HPV18 promoter (45), the E2 protein binds directly to the HPV30 promoter, causing repression of HPV30

E6 and E7 expression. Loss of the E7 protein results in the protection of p105^{Rb} and p130 from rapid proteasome-mediated degradation, leading to increased accumulation of these proteins. p105^{Rb} and p130 then bind to E2F4, protect it from the ubiquitin-proteasome pathway, and promote its relocalization to the nucleus where p105^{Rb}-E2F4 and p130-E2F4 complexes accumulate. These p105^{Rb}-E2F4 inhibitory complexes bind to E2F site 1 in the *cdc25A* promoter and impose repression. The E2 protein presumably employs a similar mechanism to repress expression of additional E2F-regulated genes necessary for G₁/S transit, including E2F1 and cyclin A (29, 41, 48, 60; Goodwin and DiMaio, submitted). Thus, once expression of the HPV oncogenes was extinguished, E2F4-Rb complexes characteristic of nonproliferating cells formed and imposed transcriptional control (6, 32, 39, 49, 51). Evidently, the alterations in E2F complexes and in the regulation of E2F-responsive genes that occur during HPV-mediated cervical carcinogenesis are reversible. The integrity of the E2F-Rb axis in cervical carcinoma cells implies that therapeutic interventions that inhibit the activity or expression of HPV oncogenes may lead to a restoration of growth control in these cancers.

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