Direct Control of Cell Cycle Gene Expression by Proto-oncogene Product ACTR, and Its Autoregulation Underlies Its Transforming Activity

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Direct Control of Cell Cycle Gene Expression by Proto-Oncogene Product ACTR, and Its Autoregulation Underlies Its Transforming Activity

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ACTR (also called AIB1 and SRC-3) was identified as a coactivator for nuclear receptors and is linked to multiple types of human cancer due to its frequent overexpression. However, the molecular mechanism of ACTR oncogenicity and its function independent of nuclear receptors remain to be defined. We demonstrate here that ACTR is required for both normal and malignant human cells to effectively enter S phase. RNA interference-mediated depletion and chromatin immunoprecipitation assays show that endogenous ACTR directly controls the expression of genes important for initiation of DNA replication, which include cdc6, cdc25A, MCM7, cyclin E, and Cdk2. Moreover, consistent with its critical role in cell cycle control, ACTR expression appears to be cell cycle regulated, which involves E2F. Interestingly, ACTR is recruited to its own promoter at the G1/S transition and activates its own expression, suggesting a positive feedback mechanism for ACTR action in the control of cell cycle progression and for its aberrant expression in cancers. Importantly, overexpression of ACTR alone transforms human mammary epithelial cells, which requires its association with E2F. These findings reveal a novel role for ACTR in cell cycle control and support the notion that the ability of aberrant ACTR to deregulate the cell cycle through E2F underlies its oncogenicity in human cancers.
59, 67). Despite these clinical studies, little was known about how elevated ACTR may induce tumorigenesis and/or promote tumor growth. By crossing SRC-3 (the mouse ortholog of ACTR) knockout mice with MMTV-α-Ha-ras transgenic mice, it was recently demonstrated that ACTR is required for oncogenic ras-induced mammary tumorigenesis (25). Interestingly, deletion of ACTR did not affect the promotional role of ovarian hormones in mammary tumor formation or the hormone-responsive gene expression in the mammary gland, suggesting that ACTR and estrogens contribute to mammary carcinogenesis through different mechanisms. Another study showed that overexpression of ACTR in multiple tissues of mice resulted in many types of malignancy, including tumor formation in the mammary gland, pituitary, uterus, lung, liver, and skin, indicating that aberrant ACTR can act as an oncogene in vivo (55). Although defects or abnormal activity in IGF-1-mediated signaling were observed in these studies, it is unclear whether deregulation of the IGF-1 pathway is the primary molecular underpinning of aberrant ACTR-induced tumorigenesis.

In our attempt to determine the potential role of ACTR in the control of breast cancer cell proliferation, we found that silencing ACTR expression inhibits the proliferation of ER-positive and -negative breast cancer cells and that overexpression of ACTR negates the growth-inhibitory effect of antiestrogens (32). Through functional analysis, we uncovered that ACTR directly interacts with E2F1 and that ectopically expressed ACTR up-regulates key cell cycle genes, including those for cyclin E1, cyclin A2, cdk2, and E2F1. We report here that endogenous ACTR directly controls the expression of genes critical for initiation of DNA replication and is required for effective G1-S progression of both normal and malignant human cells. Surprisingly, we found that ACTR gene transcription appears to be cell cycle regulated, which involves an ACTR-E2F complex. More importantly, we found that elevated ACTR transforms nonmalignant human breast epithelial cells independently of the ER but dependent on its ability to associate with E2Fs.

**MATERIALS AND METHODS**

**RNA interference (RNAi), recombinant adenovirus vectors, and plasmid constructs.** Small interfering RNA (siRNA) oligonucleotides specifically targeting ACTR and control RNA oligonucleotides were synthesized by Dharmaco with the following sequences: siACTR, 5′-GGUCUUAACCUGAGUUGUGUAAATdT-3′ (sense) and 5′-UUACCAUAGGUAAUGACCCGdTdT-3′ (antisense); control siRNA, 5′-CCUAUGGUGGUGCACUACAUAGGIdTdT-3′ (sense) and 5′-GGCUUGGAUGGGUGUACACUAGGIdTdT-3′ (antisense). Adenoviral vectors expressing ACTR, GFP, or ACTR-siRNA and GFP-siRNA were created as described before (32).

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Based on the sequence information at the National Center for Biotechnology Information EvidenceViewer for human ACTR/NCOA3, a genomic DNA frag-

ACTR ACTS AS AN IMPORTANT CELL CYCLE REGULATOR 3811
was used for an RT reaction with Moloney murine leukemia virus reverse transcriptase and oligo(dT)$_{12}$ primers. cDNAs were diluted 10-fold, and 5 μl was used for the PCRs (25 to 28 cycles). The sequences of the primers used for RT-PCR are listed in Table 1. Quantitative RT-PCR was performed as previously described (32).

**RESULTS**

**ACTR is required for proliferation of both normal and malignant human cells.** Our previous study with breast cancer cells demonstrated that ACTR overexpression abrogates the growth-inhibitory effect of antioestrogens. To determine whether endogenous ACTR functions similarly in other cell types, including nonmalignant cells, we examined the effect of acute ACTR depletion on the proliferation of a panel of different cell types. As shown in Fig. 1A, adenoviral vector-mediated RNAi specifically prevented in G2/M phase was also observed in adenovirus ACTR RNAi-infected cells (from 19.7% at 12 h to 22.9% at 48 h), suggesting that ACTR may also play a role in G2/M. To directly assess the function of ACTR in G1-to-S progression, we examined the effect of ACTR knockdown on the proliferation of malignant cells such as HeLa and T98G. Proliferation of these cells is not responsive to stimulation by hormones such as estrogen and androgen. Knocking down the high endogenous levels of ACTR strongly reduced the proliferation rate of both HeLa and T98G cells (Fig. 1C). Together, these results indicate that ACTR is required for the proliferation of both normal and malignant human cells that are nonresponsive to hormonal stimulation and are derived from different tissues. ACTR depletion strongly impedes cell entry into S phase. Next, we wish to understand whether ACTR is involved in promoting cell proliferation by controlling cell cycle progression. Asynchronously proliferating IMR-90 cells were infected with the adenoviral vector for ACTR depletion and harvested at different times for analysis of cell cycle distribution by flow cytometry. As shown in Fig. 2A, 48 h after infection, cells treated with adenovirus ACTR RNAi showed a significant decrease in the S-phase cell population (from 27% at 12 h to 10% at 48 h) with a concomitant increase in the number of G$_1$-phase cells (from 53% at 12 h to 67% at 48 h), while cells mock treated or treated with adenovirus GFP did not show a significant change in cell cycle distribution between the two points. Interestingly, a slight increase in the percentage of cells treated with adenovirus ACTR RNAi showed a significant decrease in the S-phase cell population (from 27% at 12 h to 10% at 48 h) with a concomitant increase in the number of G$_1$-phase cells (from 53% at 12 h to 67% at 48 h), while cells mock treated or treated with adenovirus GFP-RNAi displayed no significant change in cell cycle distribution between the two points. Interestingly, a slight increase in the percentage of cells in G$_2$/M phase was also observed in adenovirus ACTR RNAi-treated cells (from 19.7% at 12 h to 22.9% at 48 h), suggesting that ACTR may also play a role in G$_2$/M. To directly assess the function of ACTR in G$_1$-to-S progression, we examined the effect of ACTR depletion on DNA synthesis in synchronized cells. Cells were first deprived of serum for arrest at G$_1$/G$_0$, and infected with the adenovirus RNAi, released to reenter the cell

### Table 1. Nucleotide sequences of the PCR primers used in this study

<table>
<thead>
<tr>
<th>Primer</th>
<th>Forward sequence</th>
<th>Reverse sequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACTR-A</td>
<td>TTTTCTTCGCTTATCGCTCCAG</td>
<td>TACACAGAATGGGTTGACACAC</td>
</tr>
<tr>
<td>ACTR-B</td>
<td>GCTTTACGGCCTCAAAAGTGC</td>
<td>TTGGTCTCCTCCTATTCCCTTC</td>
</tr>
<tr>
<td>ACTR-C</td>
<td>ACCCCGGGTCTCTACTACTACTG</td>
<td>TCTTTTTCCTCCGTTGTCTC</td>
</tr>
<tr>
<td>ACTR-D</td>
<td>CTGCTTGGGCACCTCCAG</td>
<td>GCTACCGAGTGAAATCCACAG</td>
</tr>
<tr>
<td>ACTR-E</td>
<td>ACAAGACGGTGCGAGAAGAGT</td>
<td>ACTAGCTACGTGGTCAGAGAG</td>
</tr>
<tr>
<td>ACTR-F</td>
<td>CCGGGAAGGTAGTTGAGGAATAGG</td>
<td>TGGGACAAAGGGGGAAAGTGG</td>
</tr>
<tr>
<td>ACTR-G</td>
<td>ATGGGGATTTGTGGACAAAGG</td>
<td>TATTTTGGTCGGAAGGTTG</td>
</tr>
<tr>
<td>ACTR-H</td>
<td>CCGGAAATGCAGACACAG</td>
<td>CCAGAAGAGGGGAGAGGAG</td>
</tr>
<tr>
<td>Cdc25A</td>
<td>AAGAAAGGGGTCACCAAGTACG</td>
<td>AAATGAGAGGGGTAAGAAGG</td>
</tr>
<tr>
<td>Cdc6</td>
<td>CACAGAAACCACAAAGCTGCTATACG</td>
<td>CAATTGGAAGAGGTCAACAG</td>
</tr>
<tr>
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<td>GATGGAGCGGATGATACCTCTC</td>
<td>CCCAGAGGAGGGGAAAGG</td>
</tr>
<tr>
<td>E2F1</td>
<td>GCAGTGGTGGGATGGAAGAGTG</td>
<td>AAACAGGATAGTGGCAAGAG</td>
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<tr>
<td>Mmc7</td>
<td>AGCGGAAATGCAAGACACAG</td>
<td>TGGGGACAAAGGGGAAAGG</td>
</tr>
<tr>
<td>TopBP1</td>
<td>GCAGAAGAAGGGAGGCGATGTCC</td>
<td>AGGAGCAGCAGGACAGAATCCT</td>
</tr>
</tbody>
</table>

* a UTR, untranslated region. 
* b GAPDH, glyceraldehyde-3-phosphate dehydrogenase.
cycle, and pulse-labeled with BrdU. Figure 2B and C show that at 48 h after adenovirus RNAi treatment, while cells treated with the control GFP-RNAi adenovirus vector had about 26% BrdU-positive cells, cells treated with the ACTR-RNAi adenovirus vector had only about 7% BrdU-positive cells. Taken together, these results suggest that ACTR depletion strongly impedes the DNA synthesis of IMR-90 cells.

ACTR is required for the expression of genes with critical functions in DNA replication. The above finding that ACTR is required for G1-to-S progression prompted us to examine whether ACTR is required for expression of genes that are crucial for cell cycle progression. Given the observation we made previously that ACTR associates with activator E2Fs, we focused our analysis on key cell cycle genes with expression regulated by E2Fs. As shown in Fig. 3A, depletion of ACTR in IMR-90 cells resulted in a significant reduction of cyclin A2, cdk2, cdc2, and E2F1 expression at both the mRNA (part b) and protein (part a) levels. The effect on the mRNA level can be observed as early as 24 h after adenovirus ACTR RNAi treatment. Notably, cyclin D1 was not affected by ACTR depletion. We then extended our study to HeLa and T98G cells and observed a similar effect of ACTR depletion on the expression of cyclin E, cdk2, and E2F1, but not on that of cyclin A2 (Fig. 3B and data not shown).

DNA replication in eukaryotic cells involves timely expression and assembly of multiple protein complexes. The expression of a number of genes, including those for cdc6, cdc25A, and MCMs, is induced at late G1 and is regulated by E2Fs. We
thus wished to determine whether inhibition of DNA synthesis by ACTR depletion resulted from suppressed gene expressions critical for initiation of DNA replication. Results in Fig. 3B indicate that, indeed, depletion of ACTR caused a two- to fivefold decrease in cdc6, cdc25A, and MCM7 transcripts and their proteins. Interestingly, the expression of RFC3, PCNA, MCM10, cdc45, and TopBP1 was not affected under the same conditions (Fig. 3B and data not shown), suggesting that ACTR is required for a subset of E2F target genes involved in DNA replication of HeLa cells.

Endogenous ACTR is recruited to a subset of E2F target genes at G1/S. Having found that endogenous ACTR is required for the expression of a subgroup of cell cycle genes, we sought to determine whether ACTR is directly involved in transcriptional control of their expression by examining the promoter occupancy of ACTR. We thus performed ChIP assays with T98G cells that can be readily rendered quiescent and progress synchronously through the cell cycle (53). In agreement with the results from ACTR depletion, we found that endogenous ACTR protein is recruited to a region containing E2F binding sites on the promoters of cdk2, E2F1, cdc6, cdc25A, and MCM7 (Fig. 4). Importantly, the recruitment is increased significantly (three- to fourfold, depending on the target genes) as the cells enter S phase. Similar induction of recruitment is observed with E2F1. Consistent with the findings that E2F4 primarily plays a repressor role at early G1 (53), the occupancy of E2F4 decreases as cells start to proliferate. The fact that ACTR does not occupy promoters of genes with expression unaffected by ACTR depletion, such as TopBP1 and caspase 9 (Fig. 4 and data not shown), indicates that the observed induction of ACTR recruitment is promoter specific and not a simple reflection of its elevated expression during cell cycle progression (details are described below).

ACTR expression is cell cycle regulated. Overexpression of ACTR has been detected in many types of human cancers. However, how ACTR expression is regulated remains unknown. In our examination of gene expression with cells synchronized in cell cycle progression, we noticed that ACTR expression fluctuates. We therefore set up experiments to determine whether ACTR gene expression is regulated in a cell cycle-dependent manner. First, we examined ACTR expression in T98G cells during their synchronous cell cycle progression. After being released from serum deprivation, fractions of cells were analyzed for cell cycle progression and for gene expression by semiquantitative RT-PCR and Western analysis. Data from flow cytometry analysis (Fig. 5A, top part) show that cells began to enter S phase around 18 h after being released from G1/G0 and progressed through S phase during the next 6 h, as indicated by an increase in the S-phase cell population from 6.7% to 26% at the 18-h point and a further increase to nearly 90% at the 24-h point. The synchronous cell cycle progression is also evidenced by the oscillation of cyclin E1 and A2 levels, as well as the timely hyperphosphorylation of pocket

FIG. 2. ACTR depletion blocks cell entry into S phase. (A) IMR-90 cells were infected with RNAi adenovirus vectors targeting ACTR (ACTR-Ri) or GFP (GFP-Ri) or mock infected and harvested 12, 24, 36, and 48 h after infection. Fixed cells were stained with propidium iodide. Cell cycle profiles were determined by flow cytometry. (B and C) IMR-90 cells were infected with RNAi adenovirus vectors, deprived of serum for arrest at G1/G0, released to reenter the cell cycle, and then pulse-labeled with BrdU for 1 h before being harvested. Cells were first stained with anti-BrdU–FITC and then counterstained with DAPI. Results in panel B represent the 48-h time point, showing the same field of cells stained with DAPI or anti-BrdU–FITC. The percentage of BrdU-positive cells in panel C was determined by counting the BrdU-positive cells in five frames and dividing by the total number of DAPI-positive cells. Results represent averages of two independent experiments.
protein p130 (indicated by the band upshifts at the 12- and 18-h points, bottom part), as p130 is usually hyperphosphorylated by cyclin/Cdk complexes at late G1. Strikingly, ACTR expression was strongly up-regulated at mRNA level in late G1 at the 12-h point (middle part), with its protein level peaking at G1/S around the 18-h point (bottom part). Interestingly, ACTR expression was sharply attenuated after cells entered S phase. Such induction kinetics of ACTR was also observed with IMR-90 cells and closely mimics that of its interacting proteins, such as E2F1 and E2F3, but not that of TIF2, P/CCAF, and CBP (Fig. 5A and data not shown).

To rule out the possibility that the change in ACTR expres-
sion is due to the effect of growth factors in the serum and to confirm that ACTR is indeed cell cycle regulated, we synchronized cells for cell cycle progression by a protocol without altering the growth factor or serum in the medium. Thus, we treated proliferating T98G cells first with hydroxyurea (which arrests the cell cycle by inhibiting DNA synthesis) to partially synchronize T98G cells at G1/S and then released them from the block in the presence of nocodazole, which in turn blocks cells at metaphase. At different points after the drug was removed, cells were harvested for flow cytometry and gene expression analysis. As shown in Fig. 5B, top part, 9 to 12 h after being released from nocodazole treatment, cells exited mitosis and entered G1-S. At the same time, the expression of ACTR, like that of E2F1 and cyclin E, was induced to a peak level (middle and bottom parts), in agreement with the expression kinetics shown in Fig. 5A. Unlike that of ACTR, the TIF2 protein level did not appear to change. Taken together, these results suggest that ACTR expression is cell cycle regulated at the transcript level, peaking at the G1-S boundary.

**ACTR promoter is activated by E2F and ACTR itself.** To understand the molecular mechanism underlying cell cycle regulation of ACTR expression, we first examined its promoter response to E2F stimulation. Thus, a 1.6-kb genomic DNA fragment encompassing the first exon of ACTR was isolated and subcloned upstream of the luciferase reporter gene in vector pGL3. As shown in Fig. 6A, the resulting construct displayed strong promoter activity when transfected into proliferating HER cells (compare the reporter activities driven by pGL3-ACTR-1.6kb with that of 3XE2F-TK-Luc). Similar results were obtained with a shorter version of the construct, pGL3-ACTR-0.6kb. Importantly, this ACTR promoter activity can be markedly stimulated by E2F1 (about 5-fold or 15-fold, respectively, for the two promoter reporters). Since the 0.6-kb fragment confers most or all of the responsiveness to E2F stimulation, we analyzed its sequence with the PROMO databank and identified multiple putative, noncanonical E2F1 binding sites (5'-CCGCC/G-3') located in the region between -150 and +360. Similar sequences have recently been demonstrated to directly bind to E2F1 and mediate its transcriptional response (58). In light of our recent finding that ACTR can act as an E2F coactivator to control E2F target gene expression, we speculated that ACTR might be involved in the control of its own promoter via E2F. Results in Fig. 6A show that, indeed, ACTR significantly enhanced the transcription of its own promoter when tested on either the 0.6-kb or the 1.6-kb reporter construct. To determine whether ACTR acts on its own promoter through association with E2Fs, we tested the activity of a mutant form of ACTR that lacks the E2F interaction domain (EID) in the reporter gene assay. Strikingly, eliminating its interaction with E2Fs severely diminished the ability of ACTR to activate its own promoter (Fig. 6B). The mutant ACTR is expressed at a level similar to that of the wild type (see Fig. 8E). These results suggest that ACTR controls its own promoter through association with E2Fs such as E2F1.

**ACTR-E2F complex is recruited to ACTR promoter at late G1 to stimulate its expression.** To address whether the endogenous ACTR-E2F complex controls ACTR transcription in a cell cycle-dependent manner, we examined its occupancy at the ACTR promoter in cells synchronously progressing through the cell cycle. T98G cells released from serum starvation were harvested for ChIP at different times after the release. As shown in Fig. 7A, quiescent cells (at the 0-h point) had little
E2F or ACTR occupancy of the ACTR promoter. At 12 h after cells reentered the cell cycle, the occupancy of the ACTR promoter by the ACTR-E2F complex was significantly induced. By 18 h, when the majority of cells were at late G1 and a fraction of cells (24.4%) entered S phase, much stronger recruitment of the complex was observed. Strikingly, when most of the cells were in S phase (at 24 h), the ACTR-E2F occupancy was markedly decreased. This dynamic occupancy of the ACTR promoter by the ACTR-E2F complex correlates closely with the kinetics of ACTR gene expression during cell cycle progression shown in Fig. 5, supporting the notion that the E2F-ACTR complex plays an important role in cell cycle regulation of ACTR expression. To confirm that the cell cycle-regulated recruitment of the E2F-ACTR complex is specific to the proximal promoter, we examined the occupancy of E2F1, ACTR, and RNA Pol II over a 10-kb genomic DNA sequence around the promoter. We found that when T98G cells were at the G1-S boundary (the 18-h point), both E2F1 and ACTR were recruited primarily to the 1-kb promoter sequence (covered by amplicons E, F, and G), which encompasses the 0.6-kb sequence used in the reporter assays (Fig. 7B, left part). Consistent with its strong promoter activity, this 1-kb region displayed a robust Pol II occupancy in the proliferating cells, as detected by the anti-Pol II antibody. Importantly, similar occupancy by E2F1, ACTR, and Pol II was observed in asynchronously proliferating MCF7 human breast cancer cells (Fig. 7B, right part), suggesting that ACTR expression is also regulated by the E2F-ACTR complex in human breast cancer cells. To examine whether ectopic expression of ACTR can stimulate endogenous ACTR gene expression in T98G cells, we infected the cells with an adenovirus vector that expressed only the coding sequence of ACTR with a hemagglutinin (HA) tag at the 3′ end. As shown in Fig. 7C, at 48 h after infection, we observed a significant increase in the expression of the endogenous ACTR gene (detected by its 3′ untranslated region sequence) in cells infected with the ACTR adenovirus vector (A), but not with the control GFP-adenovirus vector (G). Interestingly, we did not observe any significant effect of ectopic ACTR expression on the expression of SRC-1, the other member of the p160 coactivator family, suggesting that SRC-1 is not subject to regulation by ACTR under these conditions.

Overexpression of ACTR alone transforms human mammary epithelial cells, which requires its association with E2F. Having demonstrated that ACTR plays an important role in the proliferation of a number of cell types and that ACTR autoregulation may contribute to its overexpression, a critical question to be addressed is whether ACTR overexpression alone can elicit any oncogenic effect on nonmalignant human cells. MCF10A, an ER-negative, spontaneously immortalized,
nontransformed human mammary epithelial cell line, has been
widely used to assess the oncogenic activity of many oncogenes
in in vitro cell transformation assays (10, 37, 43, 45). First, to
determine whether ACTR regulates its own expression in
MCF10A cells, we performed a ChIP assay to examine the
occupancy by ACTR and E2F1 at the ACTR promoter with
proliferating MCF10A cells maintained either in medium with
the full (100%) growth factor supplements or changed to me-
dium with 0.1% of the full supplements and maintained for 6 h.
As shown in Fig. 8A, strong occupancy by ACTR and E2F1
was detected at the ACTR promoter when cells were prolifer-
ing in the medium with full supplements, indicating that
ACTR and E2F1 are indeed involved in the control of ACTR
expression in MCF10A cells. Interestingly, deprivation of the
growth factors reduced their occupancy, suggesting that the
recruitment of ACTR and E2F1 to the ACTR promoter in
MCF10A cells is stimulated by growth factors. Next, we exam-
ined whether ACTR overexpression stimulates growth factor-independent cell proliferation. MCF10A cells infected with
the ACTR-adenovirus vector continued to proliferate. It is worth noting that when MCF10A cells were maintained in the medium with full supplements, infection with the ACTR- or GFP-adenovirus vector did not have any significant effect on their proliferation (data not shown). These results suggest that high levels of ACTR can stimulate
growth factor-independent proliferation of MCF10A cells.

To examine the activity of ACTR in cellular transformation,
MCF10A cells infected with adenovirus vectors were plated in
soft agar and observed for colony formation. As shown in Fig.
8E, recombinant adenovirus vectors mediate the expression in
MCF10A cells of the wild-type and mutant forms of ACTR (as
diagramed in panel C) at a similar level, when analyzed by
Western blotting with an anti-HA antibody (part a). The level
of ectopically expressed ACTR proteins was about threefold
higher over the endogenous ACTR, judged by the results of
Western blotting with an anti-ACTR antibody (part b; note
that the monoclonal antibody recognizes an epitope within the
E2F-interaction domain [EID] and therefore does not detect
ectopically expressed ACTR-H9004

FIG. 6. ACTR controls its own promoter through E2F1. (A) HER cells were cotransfected with the indicated reporter plasmids, expression
constructs for E2F1 or ACTR, and β-galactosidase. Luciferase activities were normalized with the β-galactosidase activities. The putative E2F
binding sites were identified with the PROMO database (http://alggen.lsi.upc.es/cgi-bin/promo_v3/promo/promoinit.cgi?dirDB=TF_8.3) and are
indicated by small bars on the schematics of the pGL3-ACTR-1.6kb and -0.6kb constructs. (B) Cells were cotransfected with the pGL3-ACTR-
0.6kb reporter and an empty vector or an expression plasmid for mutant or wild-type ACTR. The structure-function domain of ACTR is shown
in the schematic, which includes moderate sequence homology to bHLH and PAS domains, protein interaction domains for E2F (EID), nuclear
hormone receptors (RID), and CBP/p300 (CID) and a region with histone acetyltransferase (HAT) activity. WT, wild type.
ACTR-A38 containing an N-terminal truncation) showed severely diminished colony formation activity. In fact, the few colonies formed contained much fewer cells and thus were smaller than the ones formed with wild-type ACTR (Fig. 8F).

Consistent with our previous finding that the receptor interaction activity of ACTR is not involved in mediating E2F transcription (32), abolishing ACTR association with the receptors by changing the three LXXLL motifs to LXXAA in the...
FIG. 8. Transformation of human mammary epithelial cells by overexpressed ACTR requires its association with E2F. (A) Recruitment of ACTR and E2F1 to the ACTR promoter in MCF10A cells is stimulated by growth factors. Proliferating MCF10A cells maintained in DMEM/F12 with the full supplements (100%; details are in Materials and Methods) or changed to medium with 0.1% of the full supplements for 6 h (0.1%) were harvested for ChIP assay with anti-ACTR or -E2F1 antibodies. ChIP DNA was analyzed for ACTR and E2F1 occupancy at the ACTR promoter with PCR primers amplifying the F fragment as shown in Fig. 7B. (B) ACTR overexpression stimulates growth factor-independent cell proliferation. MCF10A cells maintained in six-well plates in DMEM/F12 with the full supplementation were infected with the ACTR- or GFP-adenovirus (Ad) vector at equal MOIs. Four hours later, the medium was changed to DMEM/F12 with 0.1% of the full supplements. On different days after infection, cells were harvested for proliferation analysis by cell enumeration in triplicate. (D to F) Wild-type ACTR, but not E2F association-defective mutant forms of ACTR, transforms MCF10A cells. MCF10A cells were infected with equal MOIs of adenovirus vectors for expression of GFP or different forms of ACTR as indicated in the diagram (C), harvested 24 h after infection, resuspended as individual cells
ACTR-AAA mutant appeared not to have any negative effect on colony formation in either number or size (Fig. 8D and F). These results suggest that overexpression of ACTR alone can transform human mammary epithelial cells and that the transforming activity requires the association of ACTR with E2F. Given that MCF10A cells lack ER expression and that mutant ACTR lacking receptor interaction possesses the same neoplastic transformation activity as the wild type, these results also suggest that the transforming activity of ACTR does not involve the ER.

DISCUSSION

Aberrant ACTR has been linked to multiple types of human cancer. However, the function of ACTR in the control of cell proliferation has not been well understood. In this report, we demonstrated that ACTR is required for both normal and malignant human cells to effectively enter S phase and that the underlying mechanism involves the direct control of gene expressions by ACTR that are critical for initiation of DNA replication.

ACTR functions as an important cell cycle regulator. The E2F transcription factor family plays a key role in mammalian cell cycle progression by controlling gene expression critical for G1/S and G2/M transitions (22, 62, 68). Different E2Fs, in conjunction with members of the pocket proteins, likely control a specific target gene network in a cell and tissue context-dependent manner (6, 23, 36, 53, 61). Although it is well understood how mitogenic signaling initiated by growth factors impinges on the E2F-pocket protein complex to release the transcriptional repression mediated by pRb and its family members, little is known about the process of E2F-mediated activation of gene expression. In this regard, our present study, together with our previous work, strongly supports the notion that the coactivator ACTR serves as a key mediator of the transcriptional activation by E2Fs. We found that endogenous ACTR associates with activators E2F1 and E2F3 but not with repressor E2Fs such as E2F4 and is recruited to the same region occupied by E2Fs on the E2F target genes. Its ectopic expression drives quiescent cells to reenter the cell cycle (32).

As demonstrated in this study, the induction of ACTR recruitment occurs primarily at late G1. Consistent with its timely physical presence, we found that ACTR is required for the expression of E2F target genes that are normally induced at late G1 or early S phase and have important functions in the G1-S transition (such as cyclin E and cdk2) and DNA replication (such as cdc6, cdc25A, and MCM7). Together, these findings provide a mechanistic insight into the role of ACTR in the control of the cell cycle.

Since ACTR was linked to cancer due to its overexpression, it is possible that its function to promote cell proliferation is manifested primarily by the aberrantly high levels of ACTR protein in cancer cells. Indeed, Zhou et al. recently reported that knockdown of ACTR in prostate cancer cells slowed down cell cycle progression and decreased their proliferation (67). Previous studies by others and us (28, 32) and the results reported here also indicate that high levels of ACTR are required for the proliferation of malignant cells from multiple different human cancers. Interestingly, however, when we depleted the relatively low level of ACTR in normal human fibroblast cells, we observed striking inhibitory effects on their S-phase entry and cell cycle gene expression, indicating that ACTR plays a critical role in the control of the cell cycle not only in malignant cells but also in normal human cells. Lending further support to this notion, we found that the ACTR gene itself is cell cycle regulated, with a peak induction at the G1-S boundary in both normal and cancerous human cells. Although it has been shown that several transcription cofactor proteins, including p300/CBP and PCAF, can interact with E2F, this is the first demonstration that a cofactor can play such a unique role in directly controlling cell cycle progression. Moreover, consistent with our assertion that ACTR is an important cell cycle regulator, a mouse knockout study revealed that deletion of ACTR severely impairs the ability of mouse embryo fibroblasts to proliferate in response to growth factor stimulation (60, 64).

Given the enormous complexity of cellular signaling in the control of cell growth and differentiation, it is conceivable that multiple sequence-specific transcription factors and cofactors are involved in the regulation of cell cycle gene expression. Indeed, eight members of the E2F family have been identified. Recent studies have quickly expanded the repertoire of E2F targets (6, 44). Interestingly, our analysis here suggests that only a subset of the E2F targets is under the regulation of ACTR. Thus, we found that knocking down ACTR affects the expression of cyclins E1 and E2, cdk2, cdc6, cdc25A, and MCM7 but not that of PCNA, RFC3, cdc45, and TopBP1 in HeLa cells. Likewise, our recent microarray analysis revealed that the primary effect of ACTR overexpression is on the expression of a subset of E2F target genes involved in the G1/S transition and DNA replication but not on genes involved in DNA damage/checkpoint and apoptosis (unpublished data). Since Cdc6, MCM7, and Cdc25A are required for prereplication complex formation while PCNA, RFC, and cdc45 are involved in the transition to replication, our results imply that ACTR is required specifically for the expression of genes critical for prereplication complex formation.

There can be many explanations for the cell- and promoter-specific control of E2F target genes by ACTR. One of them could be that another nuclear protein(s) modulates the association of ACTR with E2F and/or the assembly of E2F-ACTR complexes at target gene loci. Several transcription factors,
including TFE3, YY1, and TopBP1, have been shown to play a role in the choice of target genes by E2F (16, 17, 29, 47). Alternatively, the cellular context dependency of ACTR may be contributed by the multiple signal input on ACTR through its posttranslational modifications such as phosphorylation and acetylation (9, 12, 63). It is also possible that ACTR acts in combination with other enzymatic complexes that modify or remodel chromatin structure, such as CBP/p300 and the TRRAP/Tip60 complex, to coordinate the expression of cell cycle gene expression.

ACTR autoregulation as a mechanism of its aberrant expression or function in cancers. Elevated levels of ACTR gene expression have been detected in an increasing number of human cancers. Although gene amplification may account for a small fraction of aberrant ACTR, the underlying mechanism for ACTR overexpression in the majority of cancers has been poorly understood. Our finding that ACTR expression is cell cycle regulated led to our investigation of its gene regulation. Remarkably, we found that ACTR expression is controlled not only by E2F but also by its own protein. These results suggest the possibility that cell cycle deregulation in the early lesion of tumorigenesis elevates ACTR expression, which in turn enhances its own gene expression and accelerates cell cycle progression. This positive feedback loop could contribute to the complete subversion of a normal cell cycle control mechanism through the selective deregulation of a subset of E2F target genes by elevated levels of ACTR. Indeed, the majority of ACTR target genes we identified, including cyclin E (both E1 and E2), cyclin A2, E2F1, MCM7, and cdc25A, are often overexpressed in many types of cancers (4, 5, 15, 50, 66). Coexpression of ACTR with E2F1 has been found in esophageal squamous cell carcinoma (14). Conceivably, similar findings will be made with other types of cancer when both genes are examined in tumor samples. As most cancer cells have accelerated proliferation, it is not surprising that ACTR overexpression is prevalent in a broad spectrum of human cancers. Therefore, the positive feedback mechanism of ACTR expression may represent a major loop that is amplified in many types of cancers. On the other hand, the findings reported here do not rule out other possible mechanisms, such as altered protein stability (48, 65), that may contribute to the aberrant level of ACTR protein found in multiple types of human cancer.

We demonstrated for the first time that overexpression of ACTR alone can transform normal mammary epithelial cells, suggesting that overexpressed ACTR is sufficient to trigger events crucial for anchorage-independent growth, such as enhanced cell cycle progression and protection from apoptosis. Further study is needed to understand the exact downstream events of ACTR-mediated neoplastic transformation. In this respect, our data are in line with the findings from animal studies which suggest an ER-independent mechanism of ACTR action (25, 55). Importantly, our observation that the full transforming activity of overexpressed ACTR requires its association with E2F directly points to the involvement of E2F. Thus, it is plausible that aberrant ACTR up-regulates a subset of target genes of the ACTR-E2F complex to accelerate the cell cycle. Whether elevation of IGF-1 signaling by aberrant ACTR, as suggested in the animal studies, or other events are responsible for averting cells from apoptosis remains to be determined. In any event, these results support the notion that quantitative alteration of ACTR can result in a unique functional integration of distinct transcriptional control programs, which is ultimately responsible for the tumorigenesis associated with aberrant ACTR.

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