Increased Levels of the FoxM1 Transcription Factor Accelerate Development and Progression of Prostate Carcinomas in both TRAMP and LADY Transgenic Mice

Tanya V. Kalin,1,2 I-Ching Wang,1 Timothy J. Ackerson,1 Michael L. Major,1 Carol J. Detrisac,3 Vladimir V. Kalinichenko,4 Alexander Lyubimov,2 and Robert H. Costa1

1Department of Biochemistry and Molecular Genetics and 2Toxicology Research Laboratory, Department of Pharmacology, College of Medicine, University of Illinois at Chicago; 3Charles River Laboratories, Pathology Associates; and 4Department of Medicine, University of Chicago, Chicago, Illinois

Abstract
The proliferation-specific Forkhead Box M1 (FoxM1 or FoxM1b) transcription factor is overexpressed in a number of aggressive human carcinomas. Mouse hepatocytes deficient in FoxM1 fail to proliferate and are highly resistant to developing carcinogen-induced liver tumors. We previously developed a transgenic (TG) mouse line in which the ubiquitous Rosa26 promoter was used to drive expression of the human FoxM1b cDNA transgene in all mouse cell types. To investigate the role of FoxM1b in prostate cancer progression, we bred Rosa26-FoxM1b mice with both TRAMP and LADY TG mouse models of prostate cancer. We show that increased expression of FoxM1b accelerated development, proliferation, and growth of prostatic tumors in both TRAMP and LADY double TG mice. Furthermore, development of prostate carcinomas in TRAMP/Rosa26-FoxM1b double TG mice required high levels of FoxM1 protein to overcome sustained expression of the alternative reading frame tumor suppressor, a potent inhibitor of FoxM1 transcriptional activity. Depletion of FoxM1 levels in prostate cancer cell lines PC-3, LNCaP, or DU-145 by small interfering RNA transfection caused significant reduction in proliferation and anchorage-independent growth on soft agar. This phenotype was associated with increased nuclear levels of the cyclin-dependent kinase inhibitor protein p27kip1 and diminished expression of S-phase promoting cyclin A2 and M-phase promoting cyclin B1 proteins. Finally, we show that elevated levels of FoxM1 protein correlate with high proliferation rates in human prostate adenocarcinomas. Our results suggest that the FoxM1 transcription factor regulates development and proliferation of prostate tumors, and that FoxM1 is a novel target for prostate cancer treatment.

Introduction
Development of cancer is a multistep process involving gain-of-function mutations that activate signaling pathways, which stimulate cell cycle progression and cell survival (1, 2). Cancer progression also requires inactivation of tumor suppressor genes that function to arrest cell proliferation in response to oncogenic stimuli (3). Activation of the Ras/mitogen-activated protein kinase (MAPK) signaling pathway drives cell cycle progression by temporal expression of cyclin regulatory subunits, which activate their corresponding cyclin-dependent kinases (cdk) through complex formation (3, 4). Progression into DNA replication (S phase) requires phosphorylation of the retinoblastoma (Rb) protein by either the cdk4/cdk6 proteins in complex with cyclin D or cdk2 in complex with cyclin E or cyclin A2 (4). Hyperphosphorylated Rb dissociates from the E2F transcription factor and alleviates inhibition of E2F to allow transcriptional stimulation of S-phase promoting genes. The cdk inhibitor (CDKI) proteins p21Cip1 and p27Kip1 also negatively regulate cdk activity through protein complex formation, and their diminished nuclear expression is required for S-phase progression (4, 5). Activation of the cdk1/cyclin B complex is required to phosphorylate protein substrates essential for mitotic progression (4).

Expression of the alternative reading frame (ARF) tumor suppressor is induced in response to oncogenic stimuli and prevents abnormal cell proliferation through increased stability of the p53 tumor suppressor by nucleolar targeting of Mdm2 (6–8). The ARF protein also targets both the E2F1 and c-Myc transcription factors to the nucleolus, thus preventing their transcriptional activation of their target genes involved in S phase and/or transformation (9–12). Expression of the ARF protein is extinguished in a variety of tumors through DNA methylation and silencing of the ARF promoter region (3). Furthermore, ARF+/− mice are susceptible to developing spontaneous tumors (13, 14), underscoring the important role of the ARF tumor suppressor in preventing tumorigenesis.

Prostate cancer is one of the leading causes of cancer-related death among men in the North America and Western Europe (15). The transgenic (TG) adenocarcinoma of the mouse prostate (TRAMP) recapitulates multiple stages of human prostate cancer by using the probasin promoter to drive prostate epithelial cell expression of the SV40 virus large T and small t tumor antigen (Tag) oncoprotein (16, 17), which function to inactivate the tumor suppressor proteins retinoblastoma (Rb), p53, and PP2A serine/threonine–specific phosphatase (18). TRAMP TG mice develop prostate epithelial cell hyperplasia and prostatic intraepithelial neoplasia (PIN), which progresses to histologic invasive prostatic carcinomas (16, 19). In LADY TG mice, the rat probasin promoter drives prostate epithelial cell expression of only the SV40 virus large T antigen oncoprotein, and they develop multifocal, low-grade PIN that progresses to high-grade PIN and early invasive prostate carcinomas with progressive neuroendocrine differentiation (20, 21). Both the reproducible and progressive nature of...
mouse prostate cancer development in the TRAMP and LADY TG mice has provided a greater understanding of the mechanisms involved in development and progression of prostate cancer (16).

The mammalian Forkhead Box (Fox) family of transcription factors consists of >50 mammalian proteins (22, 23) that share homology in the winged helix DNA-binding domain (24). Expression of FoxM1 (or FoxM1b) is induced in all proliferating mammalian cells and tumor-derived cell lines (25–29). Liver regeneration studies with mice in which the albumin promoter-enhancer Cre recombination (Alb-Cre)–mediated conditional deletion of the FoxM1 LoxP/LoxP (fl/fl) targeted allel in adult hepatocytes showed that FoxM1 is required for hepatocyte DNA replication and mitosis (30, 31). FoxM1 was shown to be essential for diminishing nuclear accumulation of CDK1 proteins p21Cip1 and p27Kip1 and for transcription of Cdc25B phosphatase, which is essential for stimulating accumulation of CDKI proteins p21Cip1 and p27Kip1 and for transcriptions of Cdc25B phosphatase, which is essential for stimulating accumulation of CDKI proteins p21Cip1 and p27Kip1 and for transcriptions of Cdc25B phosphatase, which is essential for stimulating accumulation of CDKI proteins p21Cip1 and p27Kip1 and for transcription of Cdc25B phosphatase, which is essential for stimulating activity of M-phase promoting cdk1 (30, 32, 33). Using a well-ubiquitously expressed profile of human prostate cancer tissues, we found that FoxM1 expression levels were significantly decreased in prostate cancer tissues compared to normal prostate tissues. Furthermore, FoxM1 levels were inversely correlated with tumor stage, supporting the notion that FoxM1 expression is involved in prostate cancer progression.

**Materials and Methods**

**Transgenic mice.** Wild-type C57BL/6 mice and TRAMP TG C57BL/6 mice expressing the SV40 Tag controlled by rat probasin regulatory elements were purchased from The Jackson Laboratory (Bar Harbor, ME). Female LADY (12T-10) TG mice were obtained from Dr. Robert J. Matsakis (Vanderbilt Prostate Center, Nashville, TN). We previously described development of FVB/N TG mice in which the Rosa26 promoter drives ubiquitous expression of the human FoxM1b cDNA, and increased FoxM1b levels stimulated proliferation of pulmonary cells in response to lung injury (35).

The FoxM1 transcription factor is highly expressed in human hepatocellular carcinoma (36), intrahepatic cholangiocarcinomas (37), basal cell carcinomas (38), infiltrating ductal breast carcinomas (39), anaplastic astrocytomas, and glioblastomas (40) and in a number of other human tumors (41), suggesting that FoxM1 is involved in the proliferative expansion of many different human tumors. In this study, we show that FoxM1 protein is expressed in highly proliferative human prostate cancer. To determine the potential role of FoxM1b in prostate cancer progression, we crossed Rosa26-FoxM1b TG mice with well-established TRAMP (17) or LADY (20) TG mouse models of prostate cancer. We showed that increased expression of FoxM1b accelerated development, proliferation, and growth of prostate carcinomas in both TRAMP/ Rosa26-FoxM1b and LADY/Rosa26-FoxM1b double TG mice. Furthermore, inhibiting FoxM1 levels in human prostate cancer cell lines by small interfering RNA (siRNA) transfection significantly diminished cell proliferation and anchorage-independent growth on soft agar with altered expression of a number of cell cycle regulatory proteins. We also show that FoxM1-mediated increases in the amount of cyclin A2 expression correlates with enhanced proliferation and transformation of prostate cancer cells both in vitro and in vivo. Our results suggest that the FoxM1 transcription factor regulates development and proliferation of prostate tumors.

**Quantitative real-time reverse transcription-PCR to determine mRNA expression levels.** To prepare total RNA for quantitative real-time reverse transcription-PCR (QRT-PCR), the RNA was first digested with DNaseI (RNase free) to remove contaminating genomic DNA and then it was affinity purified on the Qiagen RNasey Micro kit (Valencia, CA). We used the Bio-Rad cDNA Synthesis kit containing both oligo-dT and random hexamer primers to synthesize cDNA from 10 μg of total RNA. The following reverse reaction mixture was used for all QRT-PCR samples: 1× of IQ SybrGreen Supermix (Bio-Rad, Hercules, CA), 200 nmol/L of each primer, and 2.5 μL of 30 μL of QRT-PCR mixture, the cDNA was amplified for 40 cycles of 95°C for 15 sec and 60°C for 1 min. The relative expression of the target genes was calculated using the 2^(-ΔΔCT) method. A syringe pipette was used to count colonies and determine the mean number of colonies ± SD.
cDNA in a 25 μL total volume. Reactions were amplified and analyzed in triplicate using a MyIQ Single Color Real-Time PCR Detection System (Bio-Rad). The annealing temperature and human and mouse primers for FoxM1 and cyclophilin and mouse ARF primers to measure mRNA levels by QRT-PCR were described previously (42). These QRT-PCR mRNA levels were normalized to human cyclophilin mRNA levels ± SD.

Western blot analysis to determine protein expression levels. Nuclear protein extracts were prepared from prostate cancer cell lines at 48 hours following siRNA transfection or mock transfection using Nuclear/Cytosol Fractionation kit (K266-100, BioVision, Mountain View, CA) following protocols provided by the manufacturer, and Western blot analysis was done as described previously (32, 42, 43). We also did Western blot analysis with prostate tissue extracts from TRAMP or Lady TG mice and TRAMP/Rosa26-FoxM1b or Lady/Rosa26-FoxM1b double TG mice. The following commercially available antibodies and dilutions were used for Western blotting: mouse anti-Ki67/p27 antibody (1:3,000), mouse anti-Cip1/p21 antibody (1:3,000; BD Biosciences, San Jose, CA), mouse anti-cyclin A2 antibody (H-432; 1:2,000; Santa Cruz Biotechnology, Inc., Santa Cruz, CA), rabbit anti-cdk2 (M2; 1:1,500; Santa Cruz Biotechnology), and mouse anti-human cyclin B1 antibody (GNS-11; 1:500; BD PharMingen, San Diego, CA). The signals from the primary antibody were amplified by HRP-conjugated goat anti-mouse IgG (Bio-Rad, Hercules, CA) and detected with Enhanced Chemiluminescence Plus (Amersham Pharmacia Biotech, Piscataway, NJ) followed by autoradiography.

Statistical analysis. We used Microsoft Excel Program to calculate SD and statistically significant differences between samples using the Student’s t test. The asterisks in each figure indicate statistically significant changes with Ps calculated by Student’s t test: *, P < 0.05; **, P ≤ 0.01; and ***, P ≤ 0.001. Ps < 0.05 were considered statistically significant.

Results

FoxM1 protein is expressed in highly proliferative human prostate adenocarcinomas. We used tissue microarray of human prostate cancers containing 17 grade 1 to 2 adenocarcinomas, 26 grade 3 adenocarcinomas, and 25 grade 4 adenocarcinomas human prostate cancers, which also contained seven adjacent normal prostate tissue. Immunohistochemical staining of this human prostate cancer tissue microarray with a COOH-terminal FoxM1 antibody revealed that expression of FoxM1 increased with the severity or grade of the human prostate adenocarcinomas. We found that 60% of grades 1 to 2, 68% of grade 3, and 80% of grade 4 human prostate adenocarcinomas stained positive for FoxM1 protein. Increased nuclear levels of FoxM1 protein were found in highly proliferative prostate adenocarcinomas as evidenced by abundant staining for PCNA (Fig. 1A-B, right; data not shown), whereas low background FoxM1 staining was detected in adjacent normal prostate tissue (Fig. 1A, left). In contrast, 34% of human prostate adenocarcinomas failed to exhibit PCNA staining (Fig. 1C, right) and correlated with low background FoxM1 staining (Fig. 1C, left). We also quantitated the number of FoxM1- and PCNA-positive nuclei in the human prostate tumor tissue microarray (Fig. 1D). This analysis revealed a correlation between increased FoxM1 staining and PCNA-positive proliferating cells in human prostate adenocarcinomas. These results indicate that highly proliferative human prostate adenocarcinomas expressed elevated levels of FoxM1 protein.

TRAMP/Rosa26-FoxM1b and LADY/Rosa26-FoxM1b double transgenic mice exhibit accelerated growth and development of prostate carcinomas. To examine whether increased expression of FoxM1 protein accelerates development and proliferation of prostate carcinomas, we bred Rosa26-FoxM1b TG mice, which ubiquitously expressed FoxM1b (35), with the well-established TRAMP (17) and LADY (20) TG mouse models of prostate cancer. We harvested and weighed prostates from male wild-type, Rosa26-FoxM1b, TRAMP and LADY single TG mice, and TRAMP/Rosa26-FoxM1b and LADY/Rosa26-FoxM1b double TG mice at the indicated two time points after birth (Fig. 2A-B). Paraffin-embedded mouse prostate sections were histologically stained with H&E to evaluate the types of prostatic tumors found in the single and double TG mice (Supplementary Fig. 1A) as described previously (44).

Analysis of prostate tissue from either TRAMP/Rosa26-FoxM1b or LADY/Rosa26-FoxM1b double TG mice established that the increased expression of the FoxM1b transcription factor

![Figure 1. FoxM1 is expressed in highly proliferative human prostate adenocarcinomas. Prostate cancer tissue arrays (US Biomax) were immunostained with FoxM1 antibody as described in Materials and Methods. A, increased nuclear levels of FoxM1 protein in human prostate adenocarcinomas (right) compared with corresponding adjacent normal prostate tissue (left). B, FoxM1 and PCNA are coexpressed in human prostate adenocarcinomas. Adjacent paraffin sections of the prostate cancer tissue array were stained with antibody specific to either FoxM1 (left) or PCNA (right) proteins. Prostate cancer tumor sections immunostained for PCNA expression were counterstained with nuclear fast red (PCNA staining regions indicated by arrows). C, FoxM1-negative tumor (left) displays diminished PCNA levels (right). D, correlation between PCNA and FoxM1 staining in human prostate carcinomas. We counted the number of FoxM1 and PCNA-positive nuclei in five fields of proliferating human prostate adenocarcinomas or normal prostate tissue. Columns, mean number of nuclei staining positive for either FoxM1 or PCNA in proliferating human adenocarcinomas versus normal prostate tissue; bars, SD. ***, P < 0.001. Magnification: ×200 (A), ×50 (B and C).](image-url)
significantly accelerated the development and progression of prostatic carcinomas in both groups of double TG mice (Table 1; Fig. 2A-B). As early as 90 days of age, 40% of the TRAMP/Rosa26-FoxM1b double TG mice exhibited prostate carcinomas, whereas the other 60% of the double TG mice developed prostate hyperplasia and PIN (Table 1; Fig. 1A). In contrast, all of the TRAMP TG mice developed only prostate hyperplasia and PINs at both time points examined (Table 1; Supplementary Fig. 1A). By 165 days of age,

![Image](TRAMP/Rosa26-FoxM1b and LADY/Rosa26-FoxM1b double TG mice exhibit accelerated growth and development of prostate carcinomas. We sacrificed TRAMP and LADY single TG or TRAMP/Rosa26-FoxM1b and LADY/Rosa26-FoxM1b double TG mice at the indicated time points. Prostate glands were collected and weighed from wild-type (WT; n = 4), Rosa26-FoxM1b (n = 7), TRAMP (n = 7) and LADY (n = 7) single TG mice, and TRAMP/Rosa26-FoxM1b (n = 12) and LADY/Rosa26-FoxM1b (n = 10) double TG mice. Prostate tissue sections were immunochemically stained with antibody specific to either the PCNA or the FoxM1 protein. A, weights of prostate glands containing carcinomas from TRAMP/Rosa26-FoxM1b double TG mice compared with those of TRAMP TG mice. Columns, mean weight of mouse prostate gland; bars, SE. Prostate weight is significantly increased in the subset of TRAMP/Rosa26-FoxM1b double TG mice that developed prostate carcinomas compared with double or single TRAMP TG mice that developed PIN. B, statistically significant increase in weight of prostate glands from LADY/Rosa26-FoxM1b double TG mice compared with those of LADY single TG mice. Columns, mean weight of mouse prostate gland; bars, SE. C, elevated number of PCNA-positive cells in TRAMP/Rosa26-FoxM1b and LADY/Rosa26-FoxM1b double TG mice. Prostate tumor sections were then counterstained with nuclear fast red (D). We counted the number of PCNA-positive cells in five random microscope fields from different mouse prostates. Columns, mean number of PCNA-positive cells; bars, SD. Statistically significant increases with Ps calculated by Student's t test (A-C): *, P < 0.05; **, P ≤ 0.01; *** P ≤ 0.002. E, nucleolar localization of FoxM1 protein in mouse prostate tumors from TRAMP/Rosa26-FoxM1b double TG mice. Prostate tumor sections from TRAMP/Rosa26-FoxM1b, and LADY/Rosa26-FoxM1b double TG mice were immunostained with antibody specific to either FoxM1 protein or the nucleolar Nucleophosmin (NPM) protein (49, 50). High magnification of FoxM1 staining in prostate carcinoma cells from TRAMP/Rosa26-FoxM1b double TG mice shows partial nucleolar staining of FoxM1 protein (middle right), which is similar to the nucleolar staining pattern of the nucleophosmin protein (bottom right). Nucleolar staining pattern (arrows). Magnification: ×100 (D and E) and ×630 (middle right and bottom right, E).
weights of the prostate glands from the TRAMP/Rosa26-FoxM1b double TG mice containing carcinomas were between 64 to 87 times greater than those from TRAMP single TG mice or TRAMP/Rosa26-FoxM1b double TG mice displaying prostate hyperplasia and PINs (Fig. 2A: Table 1). All of the LADY/Rosa26-FoxM1b double TG mice developed prostate carcinomas at both time points examined, whereas only 50% of the LADY’s single TG mice exhibited prostate carcinomas (Table 1). At 120 days of age, weights of the prostate glands from the LADY/Rosa26-FoxM1b mice were ~3.5 times greater than those of the LADY single TG mice, and these prostate tumors grew larger by 150 days of age (Fig. 2B; Table 1). No prostatic tumors, PINs, or prostate hyperplasia were found in Rosa26-FoxM1b single TG mice or wild-type mice. These results indicate that elevated expression of the FoxM1b transcription factor accelerated the development and growth of prostate tumors in TRAMP and LADY double TG mice.

**TRAMP/Rosa26-FoxM1b and LADY/Rosa26-FoxM1b double TG mice display increased proliferation of prostate carcinomas.** To correlate proliferation with FoxM1 expression in mouse prostate cancer, we used immunohistochemical staining of prostate sections with either PCNA or FoxM1 antibodies (42). This analysis revealed that prostate carcinomas from TRAMP/Rosa26-FoxM1b double TG mice displayed a 10-fold increase in PCNA-positive cells compared with those in prostate hyperplasia and PINs from TRAMP single and double TG mice (Fig. 2C and D; data not shown). A 5-fold increase in PCNA staining was found in prostate carcinomas from LADY/Rosa26-FoxM1b double TG mice compared with those of LADY single TG mice (Fig. 2C). Abundant nuclear levels of FoxM1 protein were also found in highly proliferative prostate carcinoma cells from both double TG mice (Fig. 2E), whereas diminished nuclear levels of FoxM1 protein were found in prostate hyperplasia and PINs from both TRAMP and LADY single TG mice (Fig. 2E; data not shown). These results suggest that nuclear expression of FoxM1 correlates with proliferation of prostate carcinomas.

**TRAMP/Rosa26-FoxM1b TG carcinomas display increased expression of FoxM1 mRNA and continue to express the ARF tumor suppressor.** To determine molecular mechanisms involved in development of carcinomas versus prostate hyperplasia and PINs in TRAMP/Rosa26-FoxM1b double TG mice, we used QRT-PCR analysis of RNA isolated from prostate tissue with mouse primers specific to the FoxM1 gene (42). This QRT-PCR analysis showed that TRAMP/Rosa26-FoxM1b double TG mouse prostates containing carcinomas exhibited statistically significant 6-fold increase in mRNA levels of FoxM1 compared with those containing prostate hyperplasia and PINs (Fig. 3A; \( P < 0.001 \)). Prostates from Rosa26-FoxM1b TG mice exhibited a 2-fold increase in FoxM1 mRNA levels than those of either TRAMP or LADY TG mice (Fig. 3A). However, FoxM1 protein was cytoplasmic in nonproliferating prostate epithelial cells of Rosa26-FoxM1b TG mice (Supplementary Fig. 1B), a finding consistent with previous studies (29). We also used QRT-PCR analysis to determine that prostates containing carcinomas from LADY/Rosa26-FoxM1b double TG mice expressed 3-fold higher levels of FoxM1 mRNA than those of the LADY single TG mice (Fig. 3A). These studies showed that elevated FoxM1 levels correlated with increased development of prostatic carcinomas in both TRAMP/Rosa26-FoxM1b and LADY/Rosa26-FoxM1b double TG mice.

Higher magnification of FoxM1 staining in prostate carcinoma sections from TRAMP/Rosa26-FoxM1b double TG mouse revealed nucleolar staining of the FoxM1 protein (Fig. 2E, *middle right*), which is similar to the nucleolar staining pattern of the nucleophosmin protein (Fig. 2E, *bottom right*). These results suggest that the ARF tumor suppressor targets endogenous FoxM1 protein to the nucleolus of prostate carcinoma cells (32). We therefore used QRT-PCR to measure mRNA levels of ARF in prostate glands from TRAMP/Rosa26-FoxM1b double TG mice. Consistent with the nucleolar localization of FoxM1 protein in prostate carcinoma cells (Fig. 2E), QRT-PCR analysis of ARF mRNA expression revealed that prostate glands containing carcinomas exhibited statistically significant increase in levels of ARF mRNA compared with those containing prostate hyperplasia and PINs (Fig. 3B). These results suggest that development of prostate carcinomas in TRAMP/Rosa26-FoxM1b double TG mice required high levels of FoxM1 protein to overcome sustained expression of the ARF tumor suppressor, a potent inhibitor of FoxM1 transcriptional activity (32).

**FoxM1 is essential for growth, proliferation, and transformation of prostate adenocarcinoma cell lines *in vitro***. To

---

**Table 1. Histologic analysis of prostate tumors and weight of mouse prostate**

<table>
<thead>
<tr>
<th>Diagnosis*</th>
<th>TRAMP transgenic mice</th>
<th>TRAMP/Rosa26-FoxM1b double TG mice</th>
<th>LADY TG mice</th>
<th>LADY/Rosa26-FoxM1b double TG mice</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90 d ¹</td>
<td>165 d</td>
<td>90 d</td>
<td>165 d</td>
</tr>
<tr>
<td>Prostate hyperplasia and PIN</td>
<td>100% ³ (4/4)</td>
<td>100% (3/3)</td>
<td>60% (3/5)</td>
<td>55% (5/9)</td>
</tr>
<tr>
<td>Prostate weight (g) ¹</td>
<td>0.05 ± 0.02</td>
<td>0.17 ± 0.1</td>
<td>0.03 ± 0.02</td>
<td>0.13 ± 0.03</td>
</tr>
<tr>
<td>Prostate carcinoma</td>
<td>0% (0/4)</td>
<td>0% (0/3)</td>
<td>40% (2/5)</td>
<td>44% (4/9)</td>
</tr>
<tr>
<td>Prostate weight (g)</td>
<td>NA</td>
<td>NA</td>
<td>0.44 ± 0.1</td>
<td>1.14 ± 2.5</td>
</tr>
</tbody>
</table>

Abbreviation: NA, not applicable.

¹Histologic sections of mouse prostates were stained with H&E and analyzed by a pathologist using guidelines described previously (44). The mouse prostatic tumors were separated into two groups: one group includes all the prostates with prostate epithelial cell hyperplasia and PIN, and the other group includes prostate carcinomas.

²Prostates from male mice were collected, weighed, and sectioned at two time points: 90 or 165 days for TRAMP TG mice or TRAMP/Rosa26-FoxM1b double TG mice, and 120 or 150 days for LADY TG mice or LADY/Rosa26-FoxM1b double TG mice.

³Percentage of mice with prostate hyperplasia and PIN or with prostate carcinomas.

*Reside the percentage is the number of prostates with diagnosis over the number of mouse prostate tissue examined.

Mean prostate weight (g) ± SE.
FoxM1 Accelerates Development of Prostate Carcinomas

Figure 3. Significant increase in FoxM1 mRNA levels and sustained ARF tumor suppressor mRNA expression in prostate carcinomas. A, a 6-fold increase in FoxM1 mRNA levels was found in prostate carcinomas compared with PIN in TRAMP/Rosa26-FoxM1b double TG mice. Total RNA was prepared from either prostate carcinomas (CaP) or PIN in TRAMP/Rosa26-FoxM1b and LADY/Rosa26-FoxM1b double TG mice and TRAMP or LADY single TG mice. We also prepared total RNA from normal prostate tissue from wild type (WT) and Rosa26-FoxM1b TG mice. To determine relative levels of FoxM1 mRNA, QRT-PCR was done with RNA from either prostate tissue, carcinoma, or PIN and FoxM1-specific primers. B, prostate carcinomas in TRAMP/Rosa26-FoxM1b TG mice exhibit sustained expression of ARF tumor suppressor mRNA. Total RNA was prepared from either prostate carcinomas or PIN in TRAMP/Rosa26-FoxM1b double TG mice and analyzed for mRNA levels of the ARF tumor suppressor by QRT-PCR using primers specific to mouse ARF gene. Note that ARF mRNA levels in these prostate tumors were significantly less than those found in early passage FoxM1+/− mouse embryonic fibroblasts (MEF; B), which undergo premature senescence and express high levels of nuclear ARF protein (42). Levels of cyclophilin mRNA were used to normalize expression levels of FoxM1 and ARF mRNA as described in Materials and Methods. Statistically significant increases with P determined by Student’s t test: *, P < 0.05; **, P < 0.01; ***, P < 0.001.

To determine cell cycle profiles, we did flow cytometry analysis of FoxM1-depleted LNCaP, PC-3, and DU-145 prostate cancer cell lines or cells transfected with control siP27 duplex or left untransfected. Depletion of FoxM1 levels in LNCaP and PC-3 cells caused a significant accumulation of cells in the G1 phase and a 5-fold decrease in S-phase cells compared with untransfected or siP27 transfected cells (Fig. 4C). FoxM1-depleted DU-145 cells exhibited a less severe 50% decrease in S-phase progression (Fig. 4C), a finding consistent with less efficient down-regulation of FoxM1 mRNA levels by siRNA transfection (Fig. 4A). Only slight changes in G2-M phase cells were found in the FoxM1-depleted prostate cancer cell lines (Fig. 4C).

These studies showed that siRNA-mediated depletion of FoxM1 levels in prostate cancer cell lines decreased their growth and proliferation.

All of the prostate cancer cell lines with depleted FoxM1 levels showed significant decrease in anchorage-independent growth as evidenced by a reduction in the number of cell colonies that grew on soft agar (Fig. 5A and B; ref. 32). In contrast, untransfected or siP27-transfected prostate cancer cell lines exhibited similar numbers of cell colonies using the soft agar assay (Fig. 5A-B). These results suggest that FoxM1-depleted prostate cancer cells displayed reduced transformation or anchorage-independent growth, and that diminished growth of these FoxM1-depleted cells is contributing to this reduced transformation.

Prostate cancer cells with depleted FoxM1 levels exhibited increased nuclear levels of the CDKI proteins and decreased expression of cyclin A2 and cyclin B1 proteins. Liver regeneration studies showed that FoxM1-deficient hepatocytes exhibited diminished S-phase progression through increase in nuclear levels of the CDKI proteins p21Cip1 and p27Kip1 (30, 32). FoxM1-depleted LNCaP, PC-3, or DU-145 prostate cancer cells were used to prepare nuclear extracts at 48 hours following transfection and analyzed for nuclear levels of p21Cip1 and p27Kip1 protein by Western blot analysis (Fig. 5C). Nuclear levels of CDKI inhibitor proteins were most dramatically increased in FoxM1-depleted PC-3 cells (20-fold) compared with controls, whereas a 2-fold increase in these CDKI inhibitor proteins was found in DU-145 cells with low levels of FoxM1. A 2-fold increase in nuclear levels of p27Kip1 protein was found in FoxM1-depleted LNCaP cells (Fig. 5C), whereas high levels of nuclear p21Cip1 and p27Kip1 protein were found in LNCaP cells with or without FoxM1 (Fig. 5C). These results suggest that increased nuclear expression of CDKI protein p27Kip1 contributes to reduced G1-S progression.

Western blot analysis of FoxM1-depleted prostate cancer cell lines revealed a significant reduction in nuclear levels of cyclin B1 protein (Fig. 5C), which activates cdk1 through complex formation and is critical for progression into mitosis (3, 4). Published studies have shown that increased levels of the S-phase promoting cyclin...
Discussion

The proliferation-specific FoxM1 transcription factor is overexpressed in a number of aggressive human carcinomas (36–41). Published studies showed that Alb-Cre FoxM1<sup>−/−</sup> hepatocytes fail to proliferate and are highly resistant to development of hepatic tumors in response to chemical carcinogens, and that the ARF tumor suppressor inhibits FoxM1 transcriptional activity by targeting it to the nucleolus (32, 34). To determine the role of FoxM1b in prostate cancer progression, we crossed Rosa26-FoxM1b prostate cancer cell lines, which ubiquitously express FoxM1b transgene (35), with the TRAMP (16, 17) or LADY (16, 20) TG mouse models of prostate cancer. We show that increased expression of FoxM1b significantly accelerated development, proliferation, and growth of prostate carcinomas in TRAMP/Rosa26-FoxM1b and LADY/Rosa26-FoxM1b double TG mice. Furthermore, development of prostate carcinomas in TRAMP/Rosa26-FoxM1b double TG mice required high levels of FoxM1 protein to overcome sustained expression of the ARF tumor suppressor, a potent inhibitor of FoxM1 transcriptional activity (32). We also show that elevated expression of FoxM1 protein is found in highly proliferative human prostate carcinomas correlating with the aggressiveness or grade of the human prostatic tumors. These results indicate that high levels of FoxM1 protein are associated with greater proliferation in human prostate carcinomas and thus identify FoxM1 as a novel target for prostate cancer treatment.

We showed that depletion of FoxM1 levels in PC-3, LNCaP, and DU-145 prostate cancer cell lines by siRNA transfection caused a significant decrease in cell growth and progression into DNA.
replication (S phase) and reduced transformation or anchorage-independent growth on soft agar. Diminished G1-S progression and growth rate was associated with increased nuclear levels of the CDK1 protein p21\(^{CIP1}\), which negatively regulate cdk activity through protein complex formation (4, 5). Consistent with published studies (46), LNCaP cells already exhibit high nuclear levels of p21\(^{CIP1}\) protein; therefore, the slight increase in nuclear levels of p27\(^{KIP1}\) protein in FoxM1-deficient LNCaP cells contributes to their diminished cell growth in culture. Moreover, prostate tissue from TRAMP TG mice displayed low expression levels of CDK1 proteins p21\(^{CIP1}\) and p27\(^{KIP1}\) (Fig. 5D), a finding consistent with development of larger, highly proliferative prostate carcinomas in the TRAMP/Rosa26-FoxM1b double TG mice (Fig. 2).

FoxM1-depleted prostate cancer cells also displayed reduced nuclear levels of the FoxM1 target cyclin B1 (47, 48), which activates cdk1 through complex formation and the cdk1/cyclin B1 complex phosphorlylates proteins that are critical for progression into mitosis (4). Diminished nuclear levels of cyclin B1 protein are therefore contributing to decreased cell proliferation of FoxM1-deficient cancer cells through reduced mitotic entry. Published studies have shown that increased cyclin A2 levels are responsible for cell proliferation and anchorage-independent growth on soft agar (45). A significant decrease in nuclear levels of cyclin A2 was found in all of the FoxM1-depleted prostate cancer cell lines, which correlated with reduced cell proliferation and anchorage-independent growth on soft agar. Interestingly, we found that high proliferation rates in prostate cancer cell lines correlate with reduced nuclear levels of cyclin A2 protein, contributing to decreased cell proliferation of FoxM1-deficient prostate cancer cells. We propose that prostate carcinomas from FoxM1-depleted prostate cancer cell lines display a statistically significant decrease in the number of cell colonies that grew on soft agar compared with untransfected or siP27 transfected controls.

Loss of ARF function is a critical event for tumor promotion as evidenced by extinguished expression of the ARF protein in a variety of tumors through DNA methylation and silencing of the ARF promoter region (3). Expression of ARF tumor suppressor is induced in response to oncogenic stimuli and prevents abnormal cell proliferation through stabilization of p53 tumor suppressor (6), yet expression of large T antigen, an inhibitor of both the p53 and Rb tumor suppressor proteins (18), in both TRAMP and LADY models would therefore prevent this p53-dependent cell cycle arrest by ARF. However, ARF tumor suppressor also mediates p53-independent cell cycle arrest because the mouse ARF protein targets the FoxM1, E2F1, and c-Myc transcription factors to the nucleolus, thus preventing their transcriptional activation of cell cycle regulatory genes (9–12, 32, 34, 42).

We observed that 40% to 44% of the TRAMP/Rosa26-FoxM1b double TG mice developed prostate carcinomas, whereas the remaining double TG mice displayed only prostate hyperplasia and PINs. To our surprise, we found that levels of ARF mRNA were not decreased in prostate carcinomas of TRAMP/Rosa26-FoxM1b double TG mice and that the ARF protein was functional, as evidenced by nucleolar localization of FoxM1 protein in these prostate carcinoma cells. We propose that prostate carcinomas from TRAMP/Rosa26-FoxM1b double TG mice display a significant increase in FoxM1 expression to overcome FoxM1 inhibition by the

Figure 5. Depletion of FoxM1 reduces anchorage-independent growth of prostate cancer cell colonies on soft agar. The prostate cancer cell lines PC-3, LNCaP, and DU-145 were transfected with 100 nmoL of either siFoxM1 #2 or siP27 duplexes or left untransfected. One day after transfection, the cells were trypsinized and plated on soft agar for 3 weeks to analyze the anchorage-independent cell growth as described previously (32). A, representative micrographs of LNCaP prostate cancer cell colonies on soft agar after transfection with the indicated siRNA or left untransfected. B, graph presentation of the number of prostate cancer cell colonies that grew on soft agar with or without depletion of FoxM1 or p27\(^{KIP1}\) protein levels. Triplicate plates were used to count the number of cell colonies. Columns, mean number of colonies that grow on soft agar; bars, SD. FoxM1-depleted PC-3 (**, \(P = 0.003\)), LNCaP (*) , \(P = 0.007\), or DU-145 (+, \(P = 0.03\)) prostate cancer cells displayed a statistically significant decrease in the number of cell colonies that grew on soft agar compared with untransfected or siP27 transfected controls. C, FoxM1-depleted prostate cancer cell lines exhibit increased nuclear levels of CDK1 proteins and diminished expression of cyclin A2 and cyclin B1 protein. PC-3, LNCaP, or DU-145 prostate cancer cells were transfected with siFoxM1 #2 or siP27 duplex or left untransfected (−) and nuclear extracts were prepared at 72 hours following transfection and analyzed for nuclear levels of p21\(^{CIP1}\), p27\(^{KIP1}\), cyclin A2, and cyclin B1 proteins by Western blot analysis. The protein levels of cdk2 were used as a loading control. 

D, increased proliferation in TRAMP/Rosa26-FoxM1b prostate carcinomas correlates with elevated expression of cyclin A2. Expression of p21\(^{CIP1}\), p27\(^{KIP1}\), cyclin A2, and cyclin B1 proteins was determined by Western blot analysis with prostate tissue extracts isolated at later time points from TRAMP or LADY single TG mice and TRAMP/Rosa26-FoxM1b or LADY/Rosa26-FoxM1b double TG mice.

www.aacrjournals.org 1719 Cancer Res 2006; 66: (3). February 1, 2006
ARF tumor suppressor protein. Because activation of the Ras/MAPK signaling pathway is required for high levels of FoxM1 in proliferating cells (25–29), we hypothesize that highly proliferative prostate carcinomas from these double TG mice exhibit mutations that activate the Ras/MAPK signaling pathway to stimulate FoxM1 expression.

In summary, we show that elevated levels of FoxM1 protein correlate with high proliferation rates in human prostate adenocarcinomas tumors. We show that increased expression of FoxM1b accelerated development, proliferation, and growth of prostate carcinomas in TRAMP/Rosa26 FoxM1b or LADY/Rosa26 FoxM1b double TG mice. Furthermore, inhibiting FoxM1 levels in prostate cancer cell lines by siRNA transfection significantly diminished cell proliferation and anchorage-independent growth using a soft agar assay. This phenomenon was associated with increased nuclear levels of the CDK1 protein p27Kip1 and diminished expression of cyclin A2 and cyclin B1 proteins. Our results show that the FoxM1 transcription factor regulates proliferation and growth of prostatic tumors and thus identify FoxM1 as a new target for prostate cancer treatment.

Acknowledgments

Received 9/6/2005; revised 10/26/2005; accepted 12/1/2005.

Grant support: National Institute on Aging/USPHS grant RO1 AG1824-04 (R.J. Costa).

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked advertisement in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

We thank Dr. Gail Prins for critically reviewing our article. Dr. Robert J. Matusik for providing the LADY (12T-10) TG mice, and H. Yoder, B. Shin, W.N. Yu, A. Monson, M. Reyes, C. Barr, and J. Mankovskia for excellent technical assistance.

References

Increased Levels of the FoxM1 Transcription Factor Accelerate Development and Progression of Prostate Carcinomas in both TRAMP and LADY Transgenic Mice

Tanya V. Kalin, I-Ching Wang, Timothy J. Ackerson, et al.