Gene Therapy for Prostate Cancer by Controlling Adenovirus E1a and E4 Gene Expression with PSES Enhancer

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Abstract

PSES is a chimeric enhancer containing enhancer elements from prostate-specific antigen (PSA) and prostate-specific membrane antigen (PSMA) genes that are prevalently expressed in androgen-independent prostate cancers. PSES shows strong activity equivalent to cytomegalovirus (CMV) promoter, specifically in PSA/PSMA-positive prostate cancer cells, the major cell types in prostate cancer in the absence of androgen. We developed a recombinant adenovirus (AdE4PSESE1a) by placing adenoviral E1a and E4 genes under the control of the bidirectional enhancer PSES and enhanced green fluorescent protein gene for the purpose of intratumoral virus tracking under the control of CMV promoter. Because of PSES being very weak in nonprostatic cells, including HEK293 and HER911 that are frequently used to produce recombinant adenovirus, AdE4PSESE1a can only be produced in the HER911E4 cell line which expresses both E1 and E4 genes. AdE4PSESE1a showed similar viral replication and tumor cell killing activities to wild-type adenovirus in PSA/PSMA-positive prostate cancer cells. The viral replication and tumor cell killing activities were dramatically attenuated in PSA/PSMA-negative cells. To test whether AdE4PSESE1a could be used to target prostate tumors in vivo, CWR22rv s.c. tumors were induced in nude mice and treated with AdE4PSESE1a via intratumoral and tail vein injection. Compared to tumors treated with control virus, the growth of CWR22rv tumors was dramatically inhibited by AdE4PSESE1a via tail vein injection or intratumoral injection. These data show that adenoviral replication can be tightly controlled in a novel fashion by controlling adenoviral E1a and E4 genes simultaneously with a single enhancer. (Cancer Res 2005; 65(5): 1941-51)

Introduction

Prostate cancer is the most frequently diagnosed cancer in men in the United States, with an estimated incidence of more than 916 new cases and 115 deaths per day. Frequently, patients present with locally advanced disease and/or detectable distant bone metastases at initial diagnosis. The best available treatment for patients with advanced disease is androgen ablation therapy, based on the observations of Huggins and Hodges (1) that clinical prostate cancer is under the trophic influence of male hormones. Tumor regression and improvement of clinical symptoms are temporary and inevitably the disease progresses to an androgen-independent state. Currently, no curative therapy is available for androgen-independent prostate cancers.

Gene therapy provides an attractive opportunity to target androgen-independent prostate cancer. Unlike traditional chemotheraphy, it can be designed and customized to target cancers specifically according to our understanding of the disease at a molecular level. We have shown that prostate-specific antigen (PSA) or osteocalcin promoter and human herpes simplex thymidine kinase gene-based therapy inhibits the growth of androgen-independent PSA-producing cells (2–4); however, a number of restrictions limit the efficacy of this type of gene therapy. For example, this therapy only works in proliferating tumor cells and is ineffective for slow-growing cancers like prostate cancer. We further explored prostate-restricted replicative adenoviruses as an aggressive approach to eliminate prostate metastases (5). Compared to the replication-deficient adenovirus, this approach allows the virus to propagate and infect more cells in the tumor mass, which will improve the inadequate in vivo infectivity and biodistribution of adenovirus.

The most commonly used strategy to construct a tissue/tumor-restricted replicative adenovirus (TRRA) is to place the adenoviral E1a gene under the control of tissue/tumor-specific promoters (5–7). E1a protein is central to the regulation of adenoviral gene expression and viral replication by inactivating the function of tumor suppressor pRB and transactivating late gene promoters. Theoretically, without E1a protein the expression of late gene products would be diminished, preventing propagation of the virus in the cell. Tissue/tumor-specific replication could be achieved by placing E1a gene under the control of tissue/tumor-specific promoter; however, leaky replication is frequently observed with this strategy. Controlling both E1a and E1b genes with a tissue/tumor-specific promoter further improves the tissue/tumor-specific replication of TRRAs (8, 9). Recent studies showed tight regulation of adenoviral replication by placing E1a and E4 genes under the control of two promoters that are either duplicates or distinct (10, 11). Because of the difficulty in finding two active and tightly regulated promoters for a tumor type, and the use of two copies of the same promoter might induce recombination, we developed a new strategy which places both E1a and E4 genes under the control of one single prostate-specific enhancer, PSES.

PSES contains enhancer elements from PSA and prostate-specific membrane antigen (PSMA) genes, the two best studied antigens expressed by the majority of androgen-independent prostate cancers. Delineating the regulatory mechanism of PSA and PSMA expression in androgen-independent prostate cancers, we found that the main prostate-specific enhancer activity of the

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PSA enhancer core lies within a 189-bp region called AREc3 which is located 4.2 kb upstream of the start codon (12). The main prostate-specific enhancer activity of the PSMA enhancer core lies within a 331-bp region located in the third intron of the PSMA encoding gene, called PSME(del2) (12). PSES, a combination of AREc3 and PSME(del2), showed much stronger transcriptional activity than either AREc3 or PSME(del2) alone in the presence or absence of androgen and retained tight prostate-specific activity in vitro and in vivo with an activity comparable to cytomegalovirus (CMV) promoter in PSA/PSMA-positive cells and a basal activity in all PSA/PSMA-negative cells from a variety of organ tissues (12). We believe that PSES is a better transcriptional regulator than AREc3 and PSME(del2) for developing a prostate-specific replication-competent adenovirus for patients with androgen-independent cancers.

Materials and Methods

Cells and Cell Culture. HEK293 is a transformed human embryonic kidney cell line established by Graham (13) that expresses complementing adenoviral E1 protein supporting the replication of E1-deleted recombinant adenoviruses. HEK293 was maintained in MEM (Invitrogen, Carlsbad, CA) containing 10% fetal bovine serum, 1% penicillin/streptomycin, and 1% MEM nonessential amino acids. HER911 is a human embryonic retinoblast cell immortalized with a plasmid containing adenoviral E1 gene (bp 79,578-90 of the Ad5 genome). HER911 was cultured in DMEM, supplemented with 10% fetal bovine serum and 1% penicillin/streptomycin (14). HER911E4 is an HER911 derivative that expresses adenoviral E4 protein under the control of tetO (15). HER911E4 was maintained in the same medium as HER911 supplemented with 0.1 mg/mL hygromycin B (Calbiochem, San Diego, CA) and 2 µg/mL doxycycline (Sigma, St. Louis, MO). C4-2 is an androgen-independent human prostate cancer cell line derived from LNCap that retains the expression of androgen receptor, PSA, and PSMA (16). CWR22rv is an androgen-independent prostate cancer cell line derived from an androgen-dependent human xenograft tumor, CWR22 (17). PC-3 is an androgen-independent, androgen receptor-, and PSA-negative human prostate cancer cell line derived from the bone marrow aspirates of a patient with confirmed metastatic disease (18). DU145 is an androgen-independent, androgen receptor-, and PSA-negative human prostate cancer cell line established by Stone et al. (19) from a patient with prostate cancer brain metastases. C4-2, CWR22rv, PC-3, and DU145 were all maintained in RPMI 1640 supplemented with 10% fetal bovine serum and 1% penicillin/streptomycin. MCF10A, a nontumorigenic human mammary epithelial cell line, was cultured in a 1:1 mixture of DMEM and F12 medium (DMEM-F12) in which 500 mL of medium were supplemented with 26.3 mL horse serum (Invitrogen), 500 units penicillin/streptomycin, 0.5 mol/L L-glutamine, 5.36 mg insulin, 10.75 µg EGF, 52.5 µg cholera toxin, and 250 µg hydrocortisone (20). HeLa, a human cervical carcinoma, was maintained in DMEM supplemented with 10% fetal bovine serum and 1% penicillin/streptomycin (21). LoVo, a colon cancer cell (22), was maintained in DMEM supplemented with 10% fetal bovine serum and 1% penicillin/streptomycin. All cells were refed two to three times per week with fresh growth medium and maintained at 37°C in a 5% CO2 incubator.

Construction of Recombinant Adenovirus. The recombinant adenovirus construction strategy is based on a system developed by Dr. Xavier Darlington (D.D.260, Inc., Boise, ID). The system comprises the cloning vector, pAd1020SF4a, containing the adenoviral left ITR and packaging signal (bp 1-358) and the adenovirus genome vector, pAd288, containing the right arm of the adenovirus genome from 3,504 bp to the end with the E3 region. pAd288 was modified by inserting the E1b gene (including E1b TATA box, bp 1,672-3,503) to make pAd288E1b. The right end of the adenovirus genome vector, pAd288E1b, was constructed by inserting into the EcoRI site of Ad5 (Stratagene, Cedar Creek, TX). HER911E4 was maintained in the same medium as HER911 supplemented with 0.1 mg/mL hygromycin B (Calbiochem, San Diego, CA) and 2 µg/mL doxycycline (Sigma, St. Louis, MO). The E4 enhancer region [from bp 35,461 (PacI) to 35,822 (AvrII)] was replaced by a synthetic multiple cloning site made by PCR. Then, PSES-E1a [from bp 468 (E1a TATA box) to 1,644] was cloned into pPCMV-EGFP, which was then digested with BglII to release CMV-EGFP together with the adenoviral left ITR and packaging signal (bp 1-358) and a kanamycin resistance gene (Kan1). The Kan1-ITR-EGFP-CMV fragment was then cloned into the multiple cloning site of the modified PSES-E1a [from bp 468 (E1a TATA box) to 1,644] to make pAd288SF4a-ITR-EGFP. The modified PSES-E1a [from bp 468 (E1a TATA box) to 1,644] was then cloned into the E1a TATA box, bp 1,672-3,503) to make pAd288E1b-ITR-EGFP. The modified PSES-E1a [from bp 468 (E1a TATA box) to 1,644] was then cloned into the E1a TATA box, bp 1,672-3,503) to make pAd288E1b-ITR-EGFP. The modified PSES-E1a [from bp 468 (E1a TATA box) to 1,644] was then cloned into the E1a TATA box, bp 1,672-3,503) to make pAd288E1b-ITR-EGFP. The modified PSES-E1a [from bp 468 (E1a TATA box) to 1,644] was then cloned into the E1a TATA box, bp 1,672-3,503) to make pAd288E1b-ITR-EGFP. The modified PSES-E1a [from bp 468 (E1a TATA box) to 1,644] was then cloned into the E1a TATA box, bp 1,672-3,503) to make pAd288E1b-ITR-EGFP.
gradient centrifugation. All gradient-purified viral stocks were then dialyzed against dialysis buffer (1,000 ml dialysis buffer contains 789 ml double-distilled water, 1 ml 1% MgCl2, 10 ml 1% Tris-HCl (pH 7.5), and 200 ml 50% glycerol) for 24 hours at 4°C, with three buffer changes. Aliquots of purified and dialyzed viruses were stored at −70°C for future use. The viral titer was determined by Adeno-XTM Rapid Titer System (Invitrogen) according to the instructions of the manufacturer. This kit detects the adenovirus capsid hexon protein by immunohistochemistry. Final titer was expressed as infection forming units (IFU). The viral DNA was purified by phenol/chloroform extraction and was used as a template for PCR. Four PCR (5 primers were chiseled within the E4-PSES-E1a gene cassette including E4 reverse (primer 1: ACCACTCCGAGCTGCCAAGAAAATC)-TAGGACCT), PSES reverse (primer 2: AGTACTCCGATGAAATAGT-CCAGCTTAC), and E1a reverse (primer 4: CCGGGAAAAATCTGCGAAACC). PCR was done with an initial denaturation step of 94°C for 2 minutes, followed by 35 cycles of denaturation at 94°C for 30 seconds, annealing at 50°C for 30 seconds, and extension at 72°C for 1 minute, with extension in the last cycle lasting for 10 minutes. The PCR products were analyzed on a 1% agarose gel by electrophoresis.

Adenoviral Infectivity Assay. C4-2, CWR22rv, PC-3, DU145, HeLa, LoVo, MCF10A, and HEK293 cells were seeded (2.5 × 105 cells per well) in a 12-well plate 1 day before viral infection. Cells were infected with serial doses of AdCMV-Luc (an E1/E3-deleted recombinant adenovirus carrying the luciferase reporter gene controlled by CMV promoter) from 0.05 to 37.25 multiplicity of infection (1 multiplicity of infection = 1 IFU per cell). The media were changed 24 hours after addition of the virus. The cells were harvested 48 hours after infection for luciferase assay (Promega, Madison, WI). The luciferase activities obtained were used as a reference to adjust the virus titer for each cell line to obtain a similar infectivity for the experiments. The accuracy of the above titer assay was checked by reinfecting cells with the amount of virus derived from the assay.

Western Blot Analysis. C4-2, CWR22rv, PC-3, DU145, HeLa, LoVo, and MCF10A cells were seeded in six-well plates and infected with AdE4PSESE1a and a wild-type adenovirus (Ad-wt) 1 day after cell seeding. Each cell line was infected with different amounts of virus according to the luciferase activity obtained above to achieve similar infectivities. The cells were washed with cold PBS and lysed with radioimmunoprecipitation assay buffer [1 ml modified radioimmunoprecipitation buffer supplemented with 2.5 μL proteinase inhibitors (Sigma) and 20 μL 57 mM phenylmethylsulfonyl fluoride] 24 hours after infection. Cells were collected into Eppendorf tubes and incubated on ice for 1 hour. Cell debris was spun down and the supernatant was kept at −70°C. Protein concentration was evaluated by the Bradford protein assay. The same amount of protein (5 μg) collected above was subjected to SDS-PAGE separation and electrophobolled to a nitrocellular membrane using a NOVEX gel system (Invitrogen). SeeBlue marker (Invitrogen) was used as a molecular weight indicator. The membrane was probed with an anti-adenovirus-5 E1a antibody (BD Biosciences PharMingen, San Diego, CA), followed by a horseradish peroxidase-conjugated anti-mouse immunoglobulin G secondary antibody (Santa Cruz Biotechnology, Inc., Santa Cruz, CA). Supersignal West Pico Chemiluminescent Substrate (Pierce, Rockford, IL) was used to detect the signal.

Reverse Transcription-PCR for E4 mRNA. CWR22rv, C4-2, PC-3, DU145, HeLa, LoVo, and MCF10A cells were seeded in P100 dishes (5 × 105 cells per dish) and infected with AdE4PSESE1a and Ad-wt 1 day after cell seeding (~80% cell confluency). Each cell line was infected with different doses of virus to achieve comparable infectivity as described above. Cells were washed once with cold PBS and lysed for RNA isolation using TRIzol reagent (Invitrogen). Cell lysates were scraped, collected in a 1.5 ml Eppendorf tube, pipetted up-down several times, and extracted with 200 ml chloroform. The aqueous phase was removed to a new Eppendorf tube, pipetted up-down several times, and extracted with 200 ml chloroform. The RNA of the viral supernatant was collected above was subjected to SDS-PAGE separation and electrophobolled to a nitrocellular membrane using a NOVEX gel system (Invitrogen). SeeBlue marker (Invitrogen) was used as a molecular weight indicator. The membrane was probed with an anti-adenovirus-5 E1a antibody (BD Biosciences PharMingen, San Diego, CA), followed by a horseradish peroxidase-conjugated anti-mouse immunoglobulin G secondary antibody (Santa Cruz Biotechnology, Inc., Santa Cruz, CA). Supersignal West Pico Chemiluminescent Substrate (Pierce, Rockford, IL) was used to detect the signal. Reverse transcription-PCR was done using a kit from Invitrogen. The PCR products were analyzed on a 1% agarose gel by electrophoresis. Actin expression by reverse transcription-PCR was used as an internal standard of RNA loading in each sample.

Viral Replication Assay. C4-2, CWR22rv, PC-3, DU145, HeLa, LoVo, MCF10A, and HEK293 cells were seeded in six-well plates (1 × 104 cells per well) 1 day before viral infection and subsequently infected with AdE4PSESE1a or Ad-wt. Each cell line was infected with standardized doses of virus as described above. The media were changed 24 hours later, and the viral supernatants were harvested 3 days after the infection. The cells were examined under the microscope daily for up to 5 days. Then, the titers of the harvested virus soups were checked by titer assay. HER911E4 cells were seeded in 96-well plates (5 × 103 cells per well) 1 day before viral infection. The cells were infected with serial volume dilutions of the harvested supernatants, ranging from 1 to 10−11 μL per well. A row of eight wells was used for each dose. The media were changed on day 4, and the cells were examined under the microscope on day 7. The doses of the produced viruses were shown as an LD50 value (the dilution factor that causes a cytopathic effect in at least four wells of a cell line on a 96-well plate on day 7). A tissue-specificity index was obtained by dividing the LD50 value of therapeutic viruses to that of wild-type. The value is expressed as a log10 scale, such that a value of 0 indicates the therapeutic virus has the same killing activity as wild-type virus toward a cell line. A value of −1 indicates the therapeutic virus has 10 times less killing activity than wild-type virus toward a cell line.

Cell Killing Assay. C4-2, CWR22rv, PC-3, DU145, HeLa, LoVo, MCF10A, and HEK293 cells were seeded in 96-well plates (5 × 103 cells per well) 1 day before infection. The cells were infected with serial doses, ranging from 50 to 5 × 10−5 multiplicity of infection of AdE4PSESE1a and Ad-wt. A row of eight wells was used for each dose. The media were changed on day 4, and the cells were examined under a light microscope on day 7. The viral killing activity was represented as an LD50 value. A killing activity index as wild-type virus toward a cell line. A value of 0 indicates the therapeutic virus has the same killing activity as wild-type virus toward a cell line. A value of −1 indicates the therapeutic virus has 10 times less killing activity than wild-type virus toward a cell line.

Animal Experiments. All animal methods and procedures were approved by the Indiana University School of Medicine Institutional Animal Care and Use Committee (IACUC). CWR22rv mouse tumors were established by injecting 4 × 106 cells s.c. in the flanks of athymic nude mice (6 weeks old, males). The injected mice were castrated 3 days after cellular injection. Mice with similar tumor sizes were randomized 3 weeks after injection (nine tumors from six mice for each group) and treated with 2 × 104 IFU of either AdE4PSESE1a or AdCMV-EGFP (a replication-deficient adenovirus used as a negative control) in 100 μL 1 × PBS via intratumoral injection. In addition, seven tumors from six mice were treated with 5 × 104 IFU of AdE4PSESE1a in 50 μL 1 × PBS via tail vein injection. Tumor appearance and tumor size were measured once every week with calipers, and the following formula was applied to calculate tumor volume: length x width2/2. Potential contamination of genomic DNA was dissolved in 30 μL diethyl pyrocarbonate-treated H2O and its concentration was identified. Reverse transcription-PCR was done using a kit from Invitrogen. The PCR products were analyzed on a 1% agarose gel by electrophoresis. Actin expression by reverse transcription-PCR was used as an internal standard of RNA loading in each sample.

Fluorescent Imaging. We used a Berthold LB981 NightOwl System (EG&G Berthold, Bad Wildbad, Germany) to monitor the expression of EGFP in AdE4PSESE1a- or AdCMV-EGFP-treated tumors. The Berthold LB981 NightOwl System is an optical imager used for the measurement of or near-IR emitting molecules. It contains a Peltier cooled backlit CCD camera (576 × 385 pixels) housed within a light-tight enclosure. The excitation source is filtered using an HQ 470 bandpass filter (Chroma Technology Corp., Rochingham, VT) and uniformly illuminates the field of view of the mouse. The emission spectrum is filtered using an HQ 525 bandpass filter (Chroma Technology) to enhance the GFP fluorescence relative to the autofluorescence signal from endogenous tissue. The fluorescent images of the tumor were taken immediately and on days 3, 7, 14, 21, and 28 post-viral injections. The mice were sedated (1.5 mg/kg acepromazine and torbugesic by i.m. injection), positioned in the light-tight...
monitoring of viral propagation is cloned at the left end of the adenoviral genome to allow the expression. A CMV promoter-controlled EGFP expression cassette. The viral genome was released from the cloning vector by in vivo.

with freshly prepared 3,3′ complex (Vector Laboratories) for 1 hour, washed once with PBS, stained washing with PBS, slides were incubated with avidin-biotin-peroxidase applied to slides at a dilution of 1:500 and incubated for 1 hour. After primary antibodies overnight in humidified chambers at 4°C, immunoglobulin G was used as a control. The slides were reacted with room temperature. A rabbit polyclonal antibody to adenovirus 5 (Abcam, PBS, and blocked with biotin in a humidified chamber for 15 minutes at room temperature. A rabbit polyclonal antibody to adenovirus 5 (Abcam, Cambridge, MA) was applied to slides at a dilution of 1:200. Normal rabbit immunoglobulin G was used as a control. The slides were reacted with primary antibodies overnight in humidified chambers at 4°C. After being rinsed once with PBS, a biotinylated polyclonal anti-rabbit antibody was applied to slides at a dilution of 1:500 and incubated for 1 hour. After washing with PBS, slides were incubated with avidin-biotin-peroxidase complex (Vector Laboratories) for 1 hour, washed once with PBS, stained with freshly prepared 3,3′-diaminobenzidine solution for 15 minutes, and counterstained with hematoxylin.

In situ Terminal Deoxynucleotidyl Transferase–Mediated Nick End Labeling Assay. The in situ apoptosis detection kit was purchased from Roche Diagnostics (Indianapolis, IN). Tumor tissue sections were deparaffinized using a sequential xylene protocol and rehydrated through gradients of ethanol and distilled water. Slides were treated with 10 mmol/L Tris solution containing 1 μg/mL proteinase K for 15 minutes. All slides were rinsed thrice with PBS and incubated with 100 μL terminal deoxynucleotidyl transferase–mediated nick end labeling (TUNEL) reaction mixture (or 100 μL control labeling solution for negative control) in a humid chamber at 37°C for 30 minutes. The slides were washed thrice with PBS and incubated with 100 μL TUNEL POD solution in a humid chamber at 37°C for 30 minutes. After washing with PBS, the slides were stained with freshly prepared 3,3′-diaminobenzidine solution for 10 minutes, rinsed with PBS, and counterstained with hematoxylin.

Results

PSES Restricted the Expression of E4 Gene in HEK293 and HER911, Thus Controlling Adenoviral Replication. To control adenoviral replication in a prostate-specific manner, we developed a new strategy to produce a TRA. This new strategy, illustrated in Fig. 1A, places the adenoviral E1a gene at the right end of the adenoviral genome to avoid potential interference from the adenoviral packaging signal and places the prostate-specific enhancer, PSES, between E1a and E4 genes to direct their expression. A CMV promoter-controlled EGFP expression cassette is cloned at the left end of the adenoviral genome to allow the monitoring of viral propagation in vitro and virus distribution in vivo. The viral genome was released from the cloning vector by restriction enzyme PacI digestion and transected into helper cells, HEK293, HER911, and HER911E4. Green fluorescent cells could be seen under the inverted fluorescent microscope on the day following transfection in all three cell lines (data not shown). For HER911E4, which expresses adenoviral E1a and E4 proteins, the number of green fluorescent cells increased with time and formed comet-like plaques 7 days after transfection; at the same time, cytopathic effect could be detected under a light microscope. For HEK293 and HER911 helper cells, which only express adenoviral E1 proteins, the quantity and brightness of green fluorescent cells did not change significantly with time (Fig. 1B). Under a light microscope, the appearance of cells was normal and no cytopathic effect could be detected up to 7 days after transfection. This result showed that E4 was under the tight control of PSES enhancer, which was not active in HEK293 and HER911 cells.

The gene structure of AdE4PSESe1a produced in HER911E4 was confirmed by PCR using genome DNA extracted from AdE4PSESe1a-infected cells. As shown in Fig. 2, use of E4 reverse (primer 1) and PSES reverse (primer 3) primers amplified an expected DNA fragment size of 545 bp, whereas E4 reverse (primer 1) and PSES forward (primer 2) primers did not produce a PCR product because they face the same direction. In addition, a combination of PSES forward (primer 2) and E1a reverse (primer 4) primers produced an expected DNA fragment size of 699 bp, whereas PSES reverse (primer 3) and E1a reverse (primer 4) did not produce a PCR product because they face the same direction. The above results showed that no gross rearrangement of the inserted gene occurred during virus production. AdE4PSESe1a was then amplified in HER911E4, purified by CsCl gradient method, and titered (see Materials and Methods).

Differential Adenoviral Infection Susceptibility. Because of each cell line expressing different amounts of Coxsackieadenovirus receptor for adenovirus, their adenoviral infectivities were expected to vary. Therefore, it is necessary to establish individual infection conditions for each cell line to achieve similar infectivity among cell lines (24). We conducted an experiment to normalize the susceptibility of tumor cell lines to adenoviral infection using AdCMV-Luc, an E1/E3-deleted replication-deficient adenovirus that carries a luciferase reporter gene under the control of CMV promoter. Figure 3A illustrates the various viral doses required for similar infectivity in C4-2, CWR22rv, PC-3, DU145, HeLa, LoVo, MCF10A, and HEK293. For example, C4-2 was infected with 20 virus particles per cell to test whether the different viral doses shown in Fig. 3A for each cell result in similar luciferase activity. The cells indicated above were infected with AdCMV-Luc for 48 hours, followed by luciferase assay. As shown in Fig. 3B, a similar luciferase activity (about 105 luciferase units) could be obtained among cell lines when adenoviral
infectivities were standardized. This result was applied to all subsequent in vitro experiments.

**AdE4PSESE1a Directed the Expression of E1a and E4 in PSA/PSMA-Positive Prostate Cancer Cells.** To test whether PSES enhancer could control E1a protein expression in PSA/PSMA-positive prostate cancer cells, we infected C4-2 and CWR22rv (PSA/PSMA-positive, androgen-independent prostate cancer cells) and PC-3, DU145, HeLa, LoVo, and MCF10A (PSA/PSMA-negative cells) with either AdE4PSESE1a or Ad-wt. Owing to adenoviral replication efficiency varying with each cell line, Ad-wt was used as a control for similar infectivities. Figure 4A depicts the ability of Ad-wt to direct E1a protein expression in all seven cell lines tested. On the other hand, AdE4PSESE1a directed E1a protein expression only in PSA/PSMA-positive prostate cancer cells, C4-2, and CWR22rv. E1a protein expression in PSA/PSMA-negative cells was undetectable or very low. Due to the lack of accessibility to E4-specific antibodies, reverse transcription-PCR was done to compare the expression profiles of E4 mRNA among several human prostate cancer cells and nonprostatic cancerous and normal cells. Figure 4B shows that AdE4PSESE1a expressed high amounts of E4 mRNA only in PSA/PSMA-positive prostate cancer CWR22rv and C4-2, but not in PSA/PSMA-negative PC-3, DU145, HeLa, LoVo, and MCF10A. These results not only showed that PSES retained its prostate specificity in AdE4PSESE1a but also indicated that a single enhancer core could be used to control the expression of two groups of viral genes in a bidirectional manner.

AdE4PSESE1a Propagated Selectively in PSA/PSMA-Positive Prostate Cancer Cells but Not in PSA/PSMA-Negative Cancer Cells. We did an in vitro viral replication assay to compare the viral replication efficiency of AdE4PSESE1a and Ad-wt. This would also determine whether AdE4PSESE1a could replicate selectively in the PSA/PSMA-positive prostate cancer cells. Cells were infected with AdE4PSESE1a or Ad-wt and the media were changed 24 hours post viral infection. The supernatants were harvested for titer assay 2 days after the medium change. Viral titer for AdE4PSESE1a was normalized by one for Ad-wt and values were represented as log_{10} phase. As shown in Table 1, AdE4PSESE1a propagated as efficiently as Ad-wt in PSA/PSMA-positive C4-2 and CWR22rv. On the other hand, AdE4PSESE1a showed a limited replication activity in PSA/PSMA-negative cells. Compared to Ad-wt, it produced 100-fold fewer viruses in LoVo, 500-fold fewer viruses in DU145, HeLa, and HEK293, 1,000-fold fewer viruses in PC-3, and 5,000-fold fewer viruses in MCF10A cells.

We conducted another experiment to investigate the tissue-restricted replication of AdE4PSESE1a. PSA/PSMA-positive and PSA/PSMA-negative cells were infected with AdE4PSESE1a and monitored daily under a fluorescent microscope up to 5 days. EGFP expression represented AdE4PSESE1a infection. At 1 day after infection, EGFP-expressing cells were easily detected in all cell types tested (Fig. 5). The number and intensity of green cells increased in PSA/PSMA-positive prostate cancer cells but not in PSA/PSMA-negative cells. At day 5, a comet-like patch of green cells had formed only in PSA/PSMA-positive prostate cancer cells. At the same time, we could detect virus plaques under a light microscope.
microscope. All these results showed that the replication of AdE4PSESE1a is tightly controlled by PSES and restricted to PSA/PSMA-positive cells.

**AdE4PSESE1a Showed Specific Cell Killing Ability in PSA/PSMA-Positive Cancer Cells.** To test the tissue/tumor-specific killing activity of AdE4PSESE1a, serial dilutions of AdE4PSESE1a and Ad-wt were applied to C4-2, CWR22rv, PC-3, DU145, HeLa, LoVo, A549, MCF10A, and HEK293 in 96-well plates. Cells were monitored under the microscope daily. Figure 6 presents the viral doses that cause a cytopathic effect in at least four wells of cells in a line of 96-well plates used for each dose. AdE4PSESE1a was able to kill C4-2 and CWR22rv at the same doses as Ad-wt. On the other hand, AdE4PSESE1a required 100-fold more viruses than Ad-wt to kill LoVo, 500-fold more viruses to kill DU145 and HeLa, 1,000-fold more viruses to kill PC-3, and MCF10A, and 10,000-fold more viruses to kill HEK293 cells. This result indicates that the killing activity for AdE4PSESE1a was the same as for Ad-wt in PSA/PSMA-positive cancer cells and significantly attenuated in PSA/PSMA-negative prostate cancer cells and nonprostatic cancer cells.

**Table 1. Tissue/tumor-specific replication ability of AdE4PSESE1a**

<table>
<thead>
<tr>
<th>Cell lines</th>
<th>Input doses* (IFU)</th>
<th>Output viral doses (LD50b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C4-2</td>
<td>6.6 × 10^4</td>
<td>10^6</td>
</tr>
<tr>
<td>CWR22rv</td>
<td>2 × 10^4</td>
<td>10^6</td>
</tr>
<tr>
<td>PC-3</td>
<td>2.3 × 10^5</td>
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</tr>
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</tr>
<tr>
<td>MCF10A</td>
<td>1.8 × 10^5</td>
<td>5 × 10^2</td>
</tr>
<tr>
<td>HEK293</td>
<td>3.3 × 10^5</td>
<td>5 × 10^2</td>
</tr>
</tbody>
</table>

*Input viral doses mean the virus doses used to infect cells. 
b Output viral doses mean the titered virus doses in titer assay. 

AdE4PSESE1a Was Effective against the Growth of Androgen-Independent CWR22rv Prostate Tumors. CWR22rv s.c. tumors were established in athymic nude mice as described in Materials and Methods. The mice were castrated 3 days after CWR22rv inoculation to test whether AdE4PSESE1a was able to eliminate androgen-independent tumors in a castrated host. Mice were randomized 3 weeks after cell inoculation (nine tumors from six mice in each group) and received intratumoral injections of 2 × 10^7 IFU AdE4PSESE1a or AdCMV-GFP. A replication deficient adenovirus was used as a negative control. In addition, seven tumors from six mice were treated i.v. with 5 × 10^7 IFU of AdE4PSESE1a in 50 μL PBS at 1-week intervals. Tumor sizes were monitored once a week. Figure 7A shows that tumor growth was significantly retarded in the AdE4PSESE1a-treated groups regardless of the route of viral injection compared with those in the AdCMV-GFP-treated group. Two tumors from two animals disappeared in the AdE4PSESE1a intratumoral injection group (Fig. 7A). Three tumors from three different animals disappeared in the tail-vein injection group (Fig. 7C). When tumors from the intratumoral injection group disappeared, the replication activity of AdE4PSESE1a was confirmed by titer assay.
were harvested, we observed that AdCMV-GFP- and AdE4PSESE1a-treated tumors exhibited different appearances. In the AdCMV-GFP-treated group, the tumors were big, solid, and evenly hard. On the other hand, in the AdE4PSESE1a-treated group, tumors were small with some fragmentary and necrotic cotton-shaped tissues embedded in a turbid liquid. Tumor histology revealed that small, patchy island-shaped tumor tissues were surrounded by extensive necrotic tissue inside the tumors in the AdE4PSESE1a-treated group (Fig. 8A and C). However, the periphery of the necrotic area consisted of a shallow layer of healthy tumor cells (Fig. 8C), suggesting that viruses did not reach the outer rim of the tumors, which were still growing actively. This phenomenon might contribute to a minor gain in tumor size in the very late phase of the animal experiments, especially in tumors treated by intratumoral injection (Fig. 7A).

In the AdCMV-GFP-treated group, the tumor cells were healthy and evenly distributed inside the tumors with very little necrotic tissue (Fig. 8B and D). Anti-adenovirus-5 immunohistochemical staining revealed that extensive viral infection existed throughout the treated tumors, mainly in tumor cells at the border between tumor and necrosis in AdE4PSESE1a-treated tumors (Fig. 8E). Anti-adenovirus-5 immunohistochemical staining was absent in AdCMV-GFP-treated tumors (Fig. 8E).

In situ TUNEL assays were done to detect apoptotic bodies in the AdE4PSESE1a-treated tumors. Dark-brown nuclear-staining cells were found around the border between the tumor necrosis and the tumor (Fig. 8G), indicating that programmed cell death is involved in the process of tumor killing. No dark-brown cells could be found in either the tumor or necrotic areas (Fig. 8H).

**Infection of AdE4PSESE1a Could Be Monitored via a Fluorescent Imaging System.** AdE4PSESE1a carries EGFP under the control of CMV promoter to track its infection and distribution in animal tumors via a fluorescent imaging system. The expression of EGFP in AdE4PSESE1a-treated tumors was imaged with an LB981 Molecular Light Imager (Night OWL) system (25) at 3 to 28 days after viral injection. The EGFP signal was negative right after AdE4PSESE1a injection because the adenovirus did not express enough EGFP at that time (data not shown). AdCMV-GFP-treated tumors never showed an EGFP signal compared with background. A strong signal showed up on the images 3 days after AdE4PSESE1a injection (Fig. 9A), which suggests that the virus infected the tumor cells and replicated rapidly. During the following 2 weeks, fluorescence dropped slightly. Three AdE4PSESE1a-treated (intratumoral injection) tumors showed consistent, significant EGFP signals throughout the treatment period. The data for these three tumors are shown in Fig. 9B.

**Discussion**

TRRA provides an efficient *in vivo* gene delivery method that overcomes the problems encountered in the majority of gene...
areas (H, but no dark-brown cells could be found either in the tumor or in necrosis tumors (F, C2 Anti-adenovirus-5 immunohistochemical staining was absent in nontreated G, mainly in tumor cells at the border between tumor and necrosis (revealed that extensive viral infection exists throughout the treated tumors, B, H&E AdCMV-GFP-treated sections, very little necrotic tissue could be seen C, Cancer Res 2005; 65: (5). March 1, 2005 1948 www.aacrjournals.org investigations, PSES showed high activity specifically in C4-2 and

restricted replicative adenovirus (2, 5, 7, 8). In our previous the most commonly used strategy to make a TRRA. Currently, four promoters, including kallikrein 2, PSA, rat probasin, and osteocalcin, are under extensive investigation for producing prostate-restricted replicative adenovirus (2, 5, 7, 8). In our previous investigations, PSES showed high activity specifically in C4-2 and therapy protocols. One way to construct a TRRA is by using tissue/ tumor-specific promoters to control the expression of viral regulatory proteins (26, 27). There are six early transcription units in the adenovirus backbone. The first unit to be activated after entry into the nucleus is the E1a/E1b region. The adenovirus E1a proteins play important roles in the process of adenovirus gene expression and transcription (28, 29). Tissue- or tumor-specific promoters/enhancers are used to replace the E1a promoter-enhancer region, with the rationale that expression of E1a, and therefore of the whole adenovirus transcription program, will depend on these tissue- or tumor-specific promoters (30). This is the most commonly used strategy to make a TRRA. Currently, four promoters, including kallikrein 2, PSA, rat probasin, and osteocalcin, are under extensive investigation for producing prostate-restricted replicative adenovirus (2, 5, 7, 8). In our previous investigations, PSES showed high activity specifically in C4-2 and CWR22rv PSA/PSMA-positive and androgen-independent prostate cancer cells (12). A replication-deficient recombinant adenovirus carrying the luciferase reporter gene under the control of PSES enhancer drove high luciferase activity almost exclusively in PSA/PSMA-positive prostate cancer cells regardless of androgen status. We believe that PSES has several advantages over kallikrein 2 (7), PSA (2), rat probasin (31, 32), and osteocalcin promoters (3, 4). First, PSA, promoters from kallikrein 2, and rat probasin are highly androgen-dependent and may not be the best choice for patients undergoing androgen-ablation therapy. Second, probasin is a murine PSA, and the tissue-specific activity of its promoter in humans has not been extensively tested. Third, although our study of osteocalcin promoter indicates that osteocalcin promoter is active in androgen-independent cancer cells, our data also suggest that osteocalcin promoter may be active in several other organs besides bone and requires more vigorous testing to clarify its tissue specificity (33).

Early studies of E1a-based replicative-competent adenoviruses showed various degrees of success as well as certain limitations. The success of TRRA depends on the tightness of the tissue/ tumor-restricted promoter/enhancer. Some promoters are highly influenced by the context of the vector backbone, resulting in leaky E1a expression and loss of specificity. Combinatorial control of Ad5 E1a and E1b, for example E1a under the control of probasin promoter and E1b under the control of PSA promoter, was shown to achieve better tissue-specific replication than control of E1 gene expression alone (7, 8). However, it may not be easy to find two tightly controlled tissue-specific promoters for any single tumor type, such as breast cancer. Besides, juxtaposing promoters with heterogenous sequences could result in promoter competition, squelching of transcription factors, or loss of tissue specificity (34). On the other hand, juxtaposing promoters with a homologous region could result in homologous recombination and deletion of transgenes important for viral expression. Using a single promoter to drive both E1a and E1b genes could avoid homologous recombination, promoter competition, and the squelching effect of transcription factors during gene transcription (35). However, we also experienced leaky replication with this approach depending on the promoter as well as the cell line.

Besides E1a and E1b genes, the E4 genes also play critical roles in efficient viral replication and can be controlled by a tissue/ tumor-specific promoter. The adenovirus E4 gene constitutes around 10% of the viral genome and is located at the right end of the viral genome. It encodes several regulatory proteins with pleiotropic functions. Genetic analysis has shown that E4 products are essential for productive virus infection. Removal of the E4 region severely disrupts viral gene expression in transduced cells and shows that E4 products play vital roles in viral infection. The E4 proteins are involved in several levels of regulation of cellular and viral gene expression, viral DNA replication, late viral mRNA splicing and accumulation, viral protein synthesis, host shutoff, virus assembly, E2 expression, and adeno-associated virus helper function (36–39). Several sets of differentially spliced mRNAs are generated from the E4 region during viral infection (40–43).

However, new strategies to selectively control E4 gene expression via promoter/enhancer are still uncommon. The reason may be that E4 proteins are cytotoxic (44). However, E1a and E4 targeting may synergize each other, resulting in both a highly selective TRRA and neutralization of E4 protein.
cytotoxicity. Therefore, controlling both E1a and E4 regions by a single promoter can result in a more specific viral replication. There are several reports of successfully controlling adenoviral replication by controlling the expression of E1a and E4 genes (10, 11, 30, 45). Some studies controlling adenovirus E1a and E4 genes by tissue/tumor-restricted promoters have obtained high tissue/tumor-specific targeting (11, 45, 46). For example, the adenovirus mutant ONYX-411, in which the E1a and E4 genes were driven by different copies of the human E2F promoter, showed a high selectively in retinoblastoma-deficient tumor cells (11). OVA002 has the E1a and E4 genes under the control of E2F promoter and human telomerase promoter, respectively, and shows higher tumor selectivity than OVA001, in which E1a is driven by the E2F promoter and E4 is under its own promoter (45).

Previously we showed that PSES exhibits very restricted tissue-specific activity in PSA/PSMA-positive prostate cancer cells. In this report, we constructed a TRRA AdE4PSESE1a by inserting E1a in the right end of adenoviral genome to avoid potential interference from the adenoviral packaging signal and putting PSES between E1a and E4 genes to control the expression of E1a and E4 genes simultaneously. AdE4PSESE1a showed tightly controlled replication. It cannot replicate well in all nonprostatic cancer cells tested thus far, not even in HEK293 and HER911, which express E1a and E1b proteins. AdE4PSESE1a replicated as efficiently as Ad-wt in PSA/PSMA-positive cancer cells. The diminishment of AdE4PSESE1a to replicate in HEK293 and HER911 indicates the stringent requirement of E4 proteins for efficient viral replication. We detected low levels of E4 mRNA expression in PC-3 and DU145. However, AdE4PSESE1a produced 1,000-fold fewer viruses than Ad-wt in PC-3, suggesting that adenovirus requires more E4 protein expression for efficient viral replication.

AdE4PSESE1a showed better tumor suppression activity for androgen-independent prostate tumors in castrated hosts than AdCMV-GFP. In particular, two tumors disappeared in the intratumor injection group and three tumors disappeared in the tail-vein injection group. AdE4PSESE1a has another advantage over other TRRAs. It encodes a reporter, EGFP, which allows us to track the virus infection, replication, and cell killing in vitro continuously with a fluorescent microscope. EGFP also allows us to conduct live imaging to monitor viral infection, amplification, and distribution continuously through a CCD camera, such as the Berthold LB981 NightOwl System used in this study. Figure 9A depicts a dramatic increase in EGFP expression 3 days after virus injection. We believe this is due to rapid viral replication and spreading of AdE4PSESE1a, owing to AdCMV-GFP-treated tumors not exhibiting the same phenomenon. It is quite surprising that rapid viral amplification only occurred in the first few days (Fig. 9A) and EGFP signals started to drop 5 days after virus injection. It is not clear what reduced viral replication after the first phase of acute replication. It seems that tumor growth and death rate reached a balance in the first 2 weeks after virus injection and then tumor growth rate exceeded death rate, resulting in new tumor growth (Fig. 9B). The regrowth of tumor restimulated viral replication, as indicated by a slight rebound of the EGFP signal 21 days after viral injection (Fig. 9B). The immunohistochemistry indicated persistent viral replication (Fig. 8E) for 28 days after virus injection. This result is consistent with Harrison’s report that
complete tumor responses to adenovirus d309 therapy are rarely achieved despite viral persistence in the tumor (47). For a TRRA to succeed in the clinic, it is critical to understand how viral replication is slowed down after the initial acute replication phase.

In conclusion, we developed a prostate-restricted replication defective AdE4PSESE1a, by controlling the expression of E1a and E4 genes with a chimeric prostate-specific transcriptional enhancer, PSES. AdE4PSESE1a showed similar killing and replication activities to Ad-wt in PSA/PSMA-positive androgen-dependent human prostate cancer cells, and much lower activities in PSA/PSMA-negative prostate cancer cells and nonprostate cancer cells. The inhibition of the growth of androgen-independent CWR22rv s.c. tumors in castrated animals indicated the therapeutic potential of AdE4PSESE1a for the treatment of androgen-independent cancers. This study revealed that adenoviral replication slowed down after several days of acute replication, a phenomenon that needs to be overcome to optimize the therapeutic use of TRRA. We believe that AdE4PSESE1a could be further improved by replacing the CMV-EGFP expression cassette with a therapeutic gene, such as an apoptosis inducer or a suicide gene controlled by a tissue specific promoter, to further enhance its therapeutic efficacy. This report also provides a new strategy to construct a TRRA for those tumor types that have limited tissue/tumor-specific promoters available.

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References


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