Inhibition of prostate carcinogenesis in probasin/SV40 T antigen transgenic rats by leuprorelin, a luteinizing hormone–releasing hormone agonist

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The effects of leuprorelin acetate, a luteinizing hormone-releasing hormone agonist (LHRH-A), on prostate carcinogenesis in probasin/SV40 Tag transgenic rat was investigated. Fifteen weeks after administration of 0.28 and 2.8 mg/kg leuprorelin, prostate weights and serum testosterone levels were significantly decreased compared to values for transgenic controls. Histopathological findings revealed that the incidence of prostatic adenocarcinomas was significantly reduced in ventral, dorsal and lateral lobes of the prostate, correlating with decreased expression of SV40 Tag oncoprotein as well as inhibition of DNA synthesis and proliferation of epithelial cells in neoplastic lesions of the ventral prostate. Microarray analysis further showed leuprorelin acetate to significantly inhibit testicular steroidogenesis, suppressing the expression of SV40 Tag oncoprotein and altering the expression of a large number of genes which might be involved in the inhibition of prostate cancer progression in this rat model. (*Cancer Sci* 2006; 97: 459–467)

Prostate cancer has become the most commonly diagnosed malignancy in men, and the second commonest cause of cancer death after lung neoplasms in the USA.[1] Initial treatment of prostate cancer is usually androgen-ablative therapy, radiotherapy or radical prostatectomy, and patients with early stage disease respond well. However, in many patients the therapy eventually fails and death occurs from recurrent androgen-independent prostate cancer and metastasis.

Luteinizing hormone-releasing hormone (LHRH), which is synthesized in hypothalamic neurons and secreted directly into the hypophyseal-portal blood circulation in a pulsatile manner, binds to high-affinity receptors (LHRH-R) on the gonadotrophic cells in the pituitary, stimulating the synthesis and release of luteinizing hormone (LH) and follicle-stimulating hormone (FSH), which in turn stimulate the synthesis of sex steroids by the testes. Based on the hypothalamus-pituitary-gonad hormonal relationship, LHRH analogs have been developed and used to treat prostate cancer through suppression of the pituitary release of gonadotropins to achieve a chemical castration effect. The mechanism of action is presumed to result from desensitization or downregulation of LHRH receptors in the pituitary gonadotrophs after chronic exposure to LHRH agonists and a consequent decline of gonadotropin secretion and subsequent gonadal atrophy.[2,3] However, the molecular mechanisms involved in the inhibition of prostatic carcinomas by LHRH agonists are poorly defined.

Various studies have demonstrated that LHRH analogs inhibit the proliferation of human prostate cancer cell lines and prostate cancer xenografts, and also reduce the growth of androgen-dependent and independent rat Dunning tumors, suggesting that their effects are mediated by specific LHRH receptors. This has been confirmed by detection of LHRH receptor mRNA expression in human prostate cancer cell lines and prostate cancer tissues. Therefore, activation of LHRH receptors at the prostate tumor level may represent an additional and more direct mechanism of action for antitumoral LHRH agonists.[4,5]

Leuprorelin acetate is a highly superactive agonistic analog of LHRH which is reported to inhibit pituitary gonadotropin secretion and suppress testicular steroidogenesis when administered chronically in therapeutic doses.[6,7] Leuprorelin treatment is an established effective palliative measure in men with previously untreated advanced prostatic cancer, and is therefore a reasonable non-surgical alternative in patients with prostatic disorders associated with aging.[8]

A rat transgenic model producing well-differentiated prostate adenocarcinomas in all prostatic lobes and in a short period (15 weeks of age) using the Simian virus 40 T antigen under control of the probasin gene promoter (PB/SV40 Tag) has been established in our laboratory.[9] This rat model of prostate carcinogenesis, which is completely androgen-dependent, provides a good tool to evaluate strategies for prevention and treatment of prostate cancer in a relatively short-term.

The present study was undertaken to investigate the effects of leuprorelin acetate on prostate carcinogenesis using our PB/SV40 Tag transgenic rats, with special attention to molecular changes in response to leuprorelin treatment, assessed by microarray analysis.

Materials and Methods

Animals

Heterozygous probasin-SV40 large T antigen (PB/SV40 Tag) transgenic male rats for this study were obtained by mating

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heterologous transgenic males and wild-type Sprague Dawley female rats (Clea, Tokyo, Japan). Rats weighing 110–150 g and aged 5 weeks at the commencement were used. They were ear-tagged and housed three rats per plastic cage on wood-chip bedding in an air-conditioned specific pathogen-free (SPF) animal room at 22 ± 2°C and 55 ± 5% humidity with a 12 h light/dark cycle. The animals had free access to food (Oriental MF, Oriental Yeast, Tokyo, Japan) and water. All animal experiments were performed under protocols approved by the Institutional Animal Care and Use Committee of Nagoya City University School of Medicine.

Screening of transgenic rats

DNA samples were obtained from rat tails by the proteinase K/phenol/chloroform method. Polymerase chain reaction (PCR) was performed using Taq polymerase (TaKaRa, Japan) to amplify a 300 bp fragment of SV40 Tag. Primers used were 5′-AGCCCTGTCCTCCTGCAGGAT-3′ (upper primer) and 5′-GGCCAGCCTCACGGGGTTCA-3′ (lower primer) (Hokkaido System Science, Japan).

Chemicals

Leuprorelin acetate (Leuplin) was kindly donated by Takeda Chemical Industries (Osaka, Japan) in a white powder form as a microcapsule sustained-release preparation (microspheres of 20 μm diameter). The molecular weight is 1269.47 and the chemical comprises nine amino acids and has the empiric formula of $C_{59}H_{84}N_{16}O_{12}.C_2H_4O_2$.[10]

Stock leuprorelin solution (1.875 mg/mL) was freshly prepared by suspending a vial of leuprorelin (3.75 mg leuprorelin acetate, 33.1 mg DL-lactic and glycolic acids copolymer [3:1], 0.65 mg purified gelatin and 6.6 mg D-mannitol) into 2 mL of diluent (100 mg D-mannitol, 10 mg sodium carboxymethyl cellulose and 2 mg polysorbate-80) from which two doses (high-dose; 2.8 mg/kg and low-dose; 0.28 mg/kg) were prepared and subcutaneously administered to the back of rats once every 4 weeks for a total of four injections.[11]

Study design

A total of 36 heterozygous transgenic male rats were allocated into four equally sized groups so that there were no significant differences in mean bodyweights. Group I (controls) comprised transgenic rats with the probasin/SV40 Tag serving as the reference group. Group II (vehicle) comprised PB/SV40 Tag transgenic animals which received a subcutaneous injection of the diluent (1.5 mL/kg) once every 4 weeks for a total of four injections. Group III (low-dose) comprised transgenic animals that received a subcutaneous injection of leuprorelin at 0.28 mg/kg once every 4 weeks for a total of four injections. Group IV (high-dose) comprised transgenic animals which received a subcutaneous injection of leuprorelin at 2.8 mg/kg once every 4 weeks for a total of four injections. Animal weights were recorded weekly throughout the experimental period (15 weeks).

Blood collection and tissue sampling

At the end of the treatment period (15 weeks), animals in all groups were intraperitoneally injected 1 h before being killed with 2% 5-bromo-2′-deoxyuridine solution (BrdU) at a dose of 100 mg/kg bodyweight.[12] Blood was collected from the abdominal aorta under ether anesthesia into 10 mL plastic vacuum tubes, kept on ice to clot and centrifuged. Serum samples were then analyzed for total testosterone with a direct radioimmunoassay (RIA) kit (Diagnostic Products Corporation, USA), for LH and FSH with double antibody RIA research kits (Amersham Biosciences, UK), and for urea nitrogen and creatinine levels using commercial kits (Alfresa Pharma, Japan). The urinogenital organs, comprising the prostate gland, seminal vesicles and urinary bladder were excised, weighed and photographed. Both ventral prostate lobes were separated and weighed. One lobe together with the pituitary gland was immediately frozen in liquid nitrogen then stored at −80°C until RNA extraction, while the other lobe together with the remaining prostates and tongues was fixed in 10% phosphate-buffered formalin for 48 h, routinely processed to hematoxylin and eosin (HE) stained sections and histopathologically examined. Livers, kidneys and testes were excised at necropsy and weighed.

Immunohistochemistry

Immunohistochemical analyses of androgen receptor (AR) and SV40 Tag expression were performed with a Discovery instrument using DAB Map kits (Ventana Medical Systems, USA) with polyclonal rabbit antiandrogen receptor (PA1-110, Affinity BioReagents, USA) and monoclonal mouse anti-SV40 large T antigen (554149, BD PharMingen, USA) antibodies. Binding was visualized with a Vectastain Elite ABC kit (Vector Laboratories, USA) and light hematoxylin counterstaining was conducted to facilitate microscopic examination. Furthermore, the effects of administration of leuprorelin acetate on DNA synthesis in the epithelial cells of the ventral prostates of PB/SV40 Tag transgenic rats was investigated using BrdU immunostaining using a monoclonal mouse antibromodeoxyuridine antibody (Dako, Denmark). The numbers of BrdU positive cells were counted in 1000 cells/slide and BrdU labeling indices was determined with the following equation: (number of labeled cells/number of total cells) × 100.

Extraction of RNA

Extraction of total RNA from rat ventral prostate lobes as well as pituitary glands for reverse transcription (RT)-PCR and microarray analyses was performed according to an ISOGEN protocol (Nippon Gene, Japan) with DNase treatment using a RQ1 RNase-Free DNase kit (Promega Corporation, USA). Concentration and purity of total RNAs were assessed by measuring absorbance at 260 and 280 nm with a spectrophotometer (Ultrospec 3300 pro, Amersham Pharmacia Biotech, USA) and quality was assessed with an Agilent 2100 Bioanalyzer using a RNA 6000 Nano LabChip Kit (Agilent Technologies, USA). For microarray assays, the concentration, purity and quality of RNA should be >2, with an A_{260}:A_{280} between 1.8 and 2.1, and the 28S:18S ratio should approach 2. Extracted RNA samples were stored at −80°C.

Quantitative RT-PCR analyses of mRNA expression of SV40 Tag, androgen receptor and LHRH-receptors

One microgram of RNA was converted to cDNA with avian myeloblastosis virus (AMV) reverse transcriptase (TaKaRa, Japan) in a 20 μg reaction mixture. Aliquots of 2 μg of cDNA samples were subjected to quantitative RT-PCR using

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SYBR Premix ExTaq (TaKaRa) in a light cycler apparatus (Roche Diagnostic, Mannheim, Germany). Primers used for SV40 Tag were 5′-GTCAGCAGTAGCCTCATCAT-3′ and 5′-GGTTGATTGCTACTGCTTCG-3′; primers for AR were 5′-GACTATTACTTCCCACCCCAG-3′ and 5′-ACATTTCCGGAGACGACACGA-3′; primers for LHRH-R were 5′-CTTGAAGCCCGTCCTTGGAGAAAT-3′ and 5′-GCGATCCAGGCTAATCACCACCAT-3′; and primers for rat cyclophilin (housekeeping gene) were 5′-TGCTGGACCAAACACAAATG-3′ and 5′-GAAGGGGAATGAGGAAAATA-3′. The LightCycler amplification protocol consisted of four programs: program 1, preincubation and denaturation of the template DNA (one cycle; 95°C for 30 s); program 2, amplification of the target DNA (30–40 cycles of denaturation at 95°C for 5 s, primer annealing at 45°C for SV40 Tag, 52°C for AR, 55°C for cyclophilin and 60°C for LHRH-R for 15 s and elongation at 72°C for 30 s); program 3, melting curve analysis for product identification (95°C for 0 s, 65°C for 15 s and 95°C for 0 s); and program 4, cooling of the rotor and thermal chamber (one cycle; 40°C for 30 s). Cyclophilin mRNA levels were used to normalize sample cDNA contents.

Microarray analysis of gene expression profiles

Gene expression profiling was conducted using the CodeLink Expression Bioarray System (Amersham Biosciences, USA). The CodeLink Rat Whole Genome Bioarray targets ~34 000 transcripts and Expressed Sequence Tags (ESTs) including over 29 000 well substantiated rat genes along with probes for housekeeping genes for normalization as well as positive and negative bacterial controls.

Because both low and high doses of leuprorelin showed parallel inhibition of prostatic adenocarcinoma development, the low dose was chosen for gene expression profiling analysis compared to the controls.

One RNA sample with a final concentration of 2 μg (pooled from three animals/group) was prepared and used to probe a single microarray chip. Hybridizations were performed as directed by CodeLink instructions. Briefly, mRNA was hybridized with an oligo-dT primer that contained additional sequences corresponding to one strand of T7 RNA polymerase promoter. The oligo-dT-primed mRNA was converted to single-stranded cDNA with reverse transcriptase then into double-stranded cDNA with DNA polymerase. Double-stranded cDNA was captured using QIAquick columns (QIAGEN, Germany) and served as a template for *in vitro* transcription (IVT) by T7 RNA polymerase in the presence of biotin-UTP (PerkinElmer Life Sciences, USA) to produce biotin-labeled target cRNA transcripts that were collected on RNeasy columns (QIAGEN). Target cRNA was fragmented followed by overnight hybridization with the bioarray chip in a temperature-controlled shaking incubator. Spots were visualized using Cy5-streptavidin dye conjugate and bioarrays were scanned and hybridization intensities were analyzed with CodeLink Expression Analysis software (Amersham Biosciences). The expression ratio for each gene was calculated between leuprorelin-treated transgenic animals and controls. More than a two-fold increase or decrease was regarded as a significant change (>2 as upregulated and <0.5 as downregulated). Overexpressed and downregulated genes were then annotated and grouped by function using the public database SOURCE.

Statistical analysis

The statistical significance of the incidence of neoplastic lesions in the prostates was assessed by Scheffe's analysis. Statistical analysis of differences between means was carried out using analysis of variance (ANOVA). When significant differences were obtained between means, the post-hoc Bonferroni's test for multiple comparisons was used to evaluate the statistical significance between treatment groups at the $P < 0.05$ level of significance.

Results

Effects of leuprorelin treatment on body and organ weights in PB/SV40 Tag transgenic rats

Non-significant changes in total bodyweights were recorded in vehicle or leuprorelin treated animals throughout the experiment compared to controls, demonstrating subchronic administration (15 weeks) of leuprorelin to transgenic rats to be non-toxic.

Effects of leuprorelin treatment on the gross appearance of prostate and seminal vesicles

Macroscopically, prostates of the control and vehicle treated rats showed irregular surfaces with no apparent nodule or mass formation. Treatment of rats with low and high doses of leuprorelin markedly reduced the gross weights of the prostate and seminal vesicles in comparison to control and vehicle treated animals, without any apparent difference between the two dose groups (Fig. 1, Table 1).

Effects of leuprorelin treatment on serum LH, FSH and testosterone in PB/SV40 Tag transgenic rats

PB/SV40 Tag transgenic rats treated with low and high doses of leuprorelin for 15 weeks demonstrated a significant reduction in serum total testosterone level that reached 56.8% and 82.1%, respectively. No significant changes were observed in serum LH or FSH compared to controls.

Effects of leuprorelin treatment on the incidence of neoplastic lesions in the prostate

Prostate lesions in control rats showed marked epithelial proliferation with the formation of irregular glands and luminal bridging to give cribriform patterns. The nuclei demonstrated enlargement and severe atypia, and the lesions were compatible with human adenocarcinomas and were therefore diagnosed as such. Glands with less proliferation were also observed. These exhibited crowding of stratified epithelial cells with irregular spacing and occasional luminal bridging. Although nuclear atypia were severe, basic glandular structures were maintained, similar to normal prostates, and the lesions were diagnosed as prostatic intraepithelial neoplasia (PIN), comparable with the human lesions.[9]

Adenocarcinomas were composed of atypical cells with many mitoses forming glandular and cribriform structures. Histopathological examination revealed a 100% incidence of prostate adenocarcinomas in the ventral, lateral and anterior lobes at 20 weeks of age in the control and vehicle treated groups (Table 2), whereas the incidence was 55.6% and 66.7% in the dorsal prostate lobes, respectively. Low and high doses of leuprorelin significantly reduced the incidence

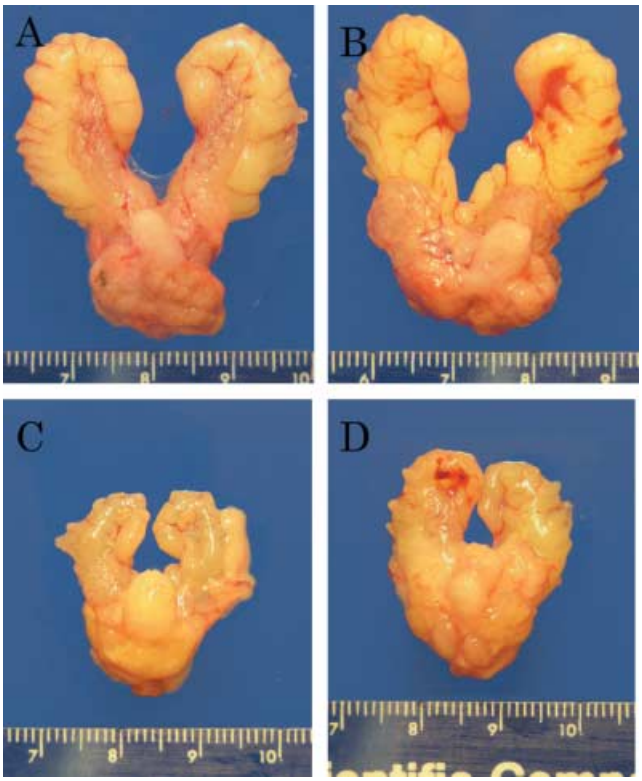

Fig. 1. Photomicrographs showing the macroscopic appearance of urogenital organs in the different groups after 15 weeks of treatment. (A) Controls; (B) vehicle-treated group; (C) low-dose leuprorelin group; (D) high-dose leuprorelin group. Macroscopically, prostates of the control and vehicle-treated rats showed irregular surfaces with no apparent nodule or mass formations. Treatment of rats with low and high doses of leuprorelin markedly reduced the gross weights of the prostate and seminal vesicle, with respect to control and vehicle-treated animals, without any significant difference between the two dose groups.

of prostatic adenocarcinomas in the ventral and lateral lobes (11.1 and 33.3%, and 11.1 and 22.2%, respectively) while causing non-significant change in the anterior lobe, with respect to controls. As for the dorsal prostate, complete inhibition of prostatic adenocarcinoma development was observed. However, no significant differences were found regarding the incidence of prostatic adenocarcinoma in the different prostatic lobes between the two dose groups.

Atrophic glands were also observed following treatment of transgenic rats with both doses of leuprorelin (Fig. 2), characterized by reduced epithelium and infiltration of inflammatory cells, most frequently observed in the high-dose group. Small cell carcinomas were also found in the lateral prostates of two rats (in the control and high-dose groups) and in the dorsal prostate of one rat (in the high-dose group).

Effects of leuprorelin treatment on androgen receptor and SV40 Tag protein expression

Expression of SV40 Tag and AR proteins was detected in almost all nuclei of the atypical epithelial cells of different prostatic lobes in the control and vehicle treated groups. Treatment of PB/SV40 Tag transgenic animals with low and high doses of leuprorelin acetate significantly reduced SV40 Tag expression in the ventral, dorsal and lateral lobes as well as AR expression in the dorsal prostate, compared to controls. Both SV40 Tag and AR expression was slightly decreased in the anterior prostate following leuprorelin treatment.

Effects of leuprorelin treatment on DNA synthesis in the ventral prostate of leuprorelin-treated rats

Subcutaneous administration of leuprorelin at low and high doses for 15 weeks to male PB/SV40 Tag transgenic rats caused significant parallel reduction in DNA synthesis in the epithelial cells of the ventral prostates compared to controls, as demonstrated by the decrease in the BrdU

Table 1. Statistical significance of the absolute and relative weight of urogenital organs (prostate, seminal vesicles and urinary bladder) as well as different prostatic lobes of PB/SV40 Tag transgenic rats treated with low and high doses of leuprorelin (15 weeks)

Group	No. of rats	Urogenital organs		Ventral prostate		Dorsolateral prostate		Anterior prostate and seminal vesicles	
		Absolute (g)	Relative (%)	Absolute (g)	Relative (%)	Absolute (g)	Relative (%)	Absolute (g)	Relative (%)
Control	9	5.33 ± 1.34	1.05 ± 0.24	0.58 ± 0.13	0.11 ± 0.02	1.48 ± 0.59	0.29 ± 0.11	3.15 ± 0.73	0.62 ± 0.13
Vehicle	9	5.03 ± 0.60	1.02 ± 0.16	0.48 ± 0.09	0.10 ± 0.02	1.22 ± 0.20	0.25 ± 0.05	3.01 ± 0.48	0.61 ± 0.12
Low-dose	9	1.71 ± 0.57*	0.35 ± 0.12*	0.14 ± 0.06*	0.03 ± 0.01*	0.53 ± 0.14*	0.11 ± 0.03*	0.94 ± 0.28*	0.19 ± 0.05*
High-dose	9	1.97 ± 0.81*	0.40 ± 0.15*	0.18 ± 0.07*	0.04 ± 0.01*	0.64 ± 0.23*	0.13 ± 0.05*	0.93 ± 0.50*	0.19 ± 0.09*

Values are mean ± SD. *Bonferroni's test was used for multiple comparisons, $P < 0.05$ is regarded as significant. Groups sharing the same characters are not significantly different.

Table 2. Incidence of prostatic adenocarcinomas in the different prostatic lobes of PB/SV40 Tag transgenic rats treated with low and high doses of leuprorelin (15 weeks)

Group	No of rats	Ventral			Lateral			Dorsal			Anterior	
		LG PIN	HG PIN	AC	LG PIN	HG PIN	AC	LG PIN	HG PIN	AC	PIN	AC
Control	9	0	0	9 (100%)	0	0	9 (100%)**	0	4 (44.4%)	5 (55.6%)	0	9 (100%)
Vehicle	9	0	0	9 (100%)	0	0	9 (100%)	0	3 (33.3%)	6 (66.7%)	0	9 (100%)
Low-dose	9	3 (33.3%)	5 (55.6%)	1 (11.1%)*	1 (11.1%)	7 (77.8%)	1 (11.1%)*	2 (22.2%)	7 (77.8%)	0*	3 (33.3%)	6 (66.7%)
High-dose	9	2 (22.2%)	4 (44.4%)	3 (33.3%)*	2 (22.2%)	5 (55.6%)	2 (22.2%)*,**	3 (33.3%)	6 (66.7%)	0*,**	2 (22.2%)	7 (77.8%)

*P value is significant at the 0.05 level by Scheffe's analysis. Groups sharing the same characters are not significantly different. **One case was diagnosed as small cell carcinoma. Percentage is shown in parentheses. AC, adenocarcinoma; HG PIN, high-grade prostatic intraepithelial; LG PIN, low-grade prostatic intraepithelial neoplasia.

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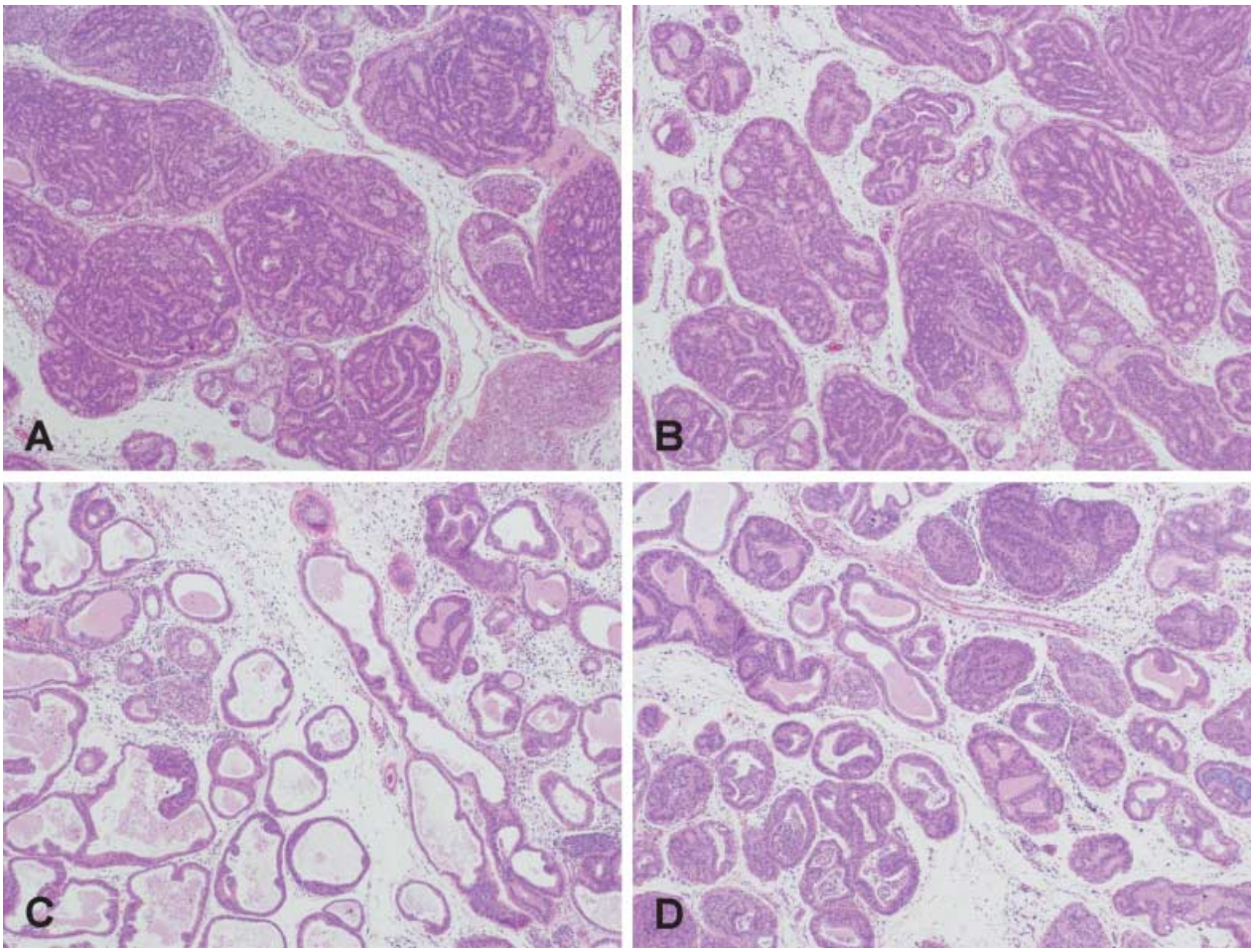

Fig. 2. Photomicrographs showing the histopathology of the ventral prostates of (A) control rats; (B) vehicle-treated group; (C) low-dose treated group; and (D) high-dose treated group. (A) and (B) show well-differentiated adenocarcinoma composed of atypical epithelial cells forming glandular and cribriform structures. (C) and (D) show that intraepithelial proliferation was markedly decreased and the relative volume of stroma was increased, prostatic intraepithelial neoplasia (PIN) is evident. Atrophic glands characterized by reduced epithelium with fibrosis and infiltration of inflammatory cells (including neutrophils, lymphocytes and macrophages) are also shown (hematoxylin and eosin, × 40).

labeling indices that reached 61.2% and 59.4%, respectively. However, no significant change in the BrdU labeling index was found between the two dose groups (Fig. 3).

Effects of leuprorelin treatment on quantitative expression of androgen receptor and SV40 Tag in the ventral prostate

RT-PCR results revealed that administration of low and high doses of leuprorelin for 15 weeks to PB/SV40 Tag transgenic rats produced a significant parallel reduction in the relative mRNA expression of SV40 Tag in the ventral prostates (87.3 and 80.0%, respectively) (Fig. 4), whereas AR expression was not significantly changed in comparison with controls (data not shown).

Effect of leuprorelin administration on the quantitative expression of LHRH-R in the pituitaries of PB/SV40 Tag transgenic rats

Expression of LHRH-R was reduced in the pituitaries of leuprorelin-treated animals, compared to untreated transgenic controls (Fig. 5). However, no significant differences were recorded in the aforementioned parameters with respect to untreated transgenic animals.

Effects of leuprorelin treatment on gene expression profiles in the ventral prostate of PB/SV40 Tag transgenic rats

Microarray analyses revealed 390 overexpressed and 655 downregulated genes (annotated and easily classified examples). Representative results are summarized in Tables 3 and 4.

Discussion

The present study demonstrated clear inhibitory effects of a LHRH agonist, leuprorelin acetate, on prostate oncogenesis in PB/SV40 Tag transgenic rats, in line with the conclusion that androgen ablation therapy continues to be the best approach for treatment of disseminated carcinomas of the prostate in the earliest androgen-responsive stages. Inhibition was achieved without any significant changes in total

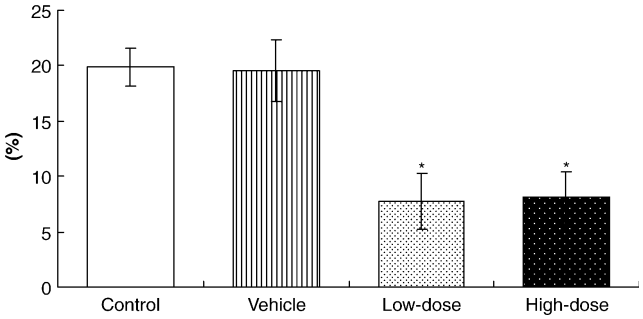

Fig. 3. Statistical significance of DNA synthesis (BrdU labeling indices) in epithelial cells of the ventral prostates of control, vehicle- and leuprorelin-treated PB/SV40 Tag transgenic rats. *$P < 0.05$ *versus* control and vehicle groups (Bonferroni's test). Values are mean ± SD.

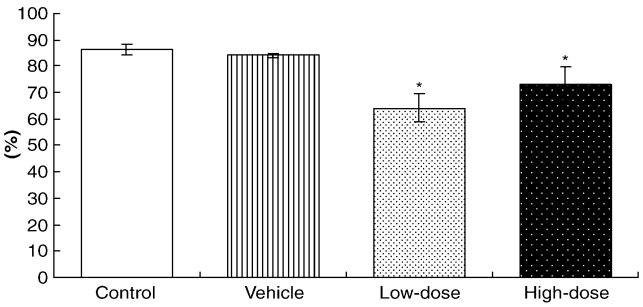

Fig. 4. Statistical significance of relative mRNA expression levels of SV40 Tag proteins compared with cyclophilin expression in the ventral prostates of control, vehicle- and leuprorelin-treated PB/SV40 Tag transgenic animals. *$P < 0.05$ *versus* control and vehicle groups (Bonferroni's test). Values are mean ± SE.

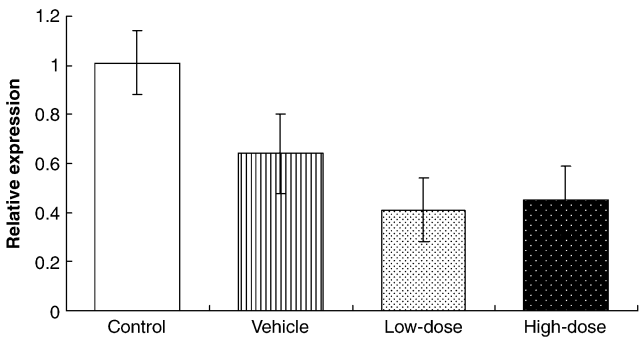

Fig. 5. Relative mRNA expression level of luteinizing hormone-releasing hormone receptor (LHRH-R) compared with cyclophilin expression in the pituitaries of untreated, vehicle- and leuprorelin-treated PB/SV40 Tag transgenic animals.Values are mean ± SE.

bodyweights and absolute or relative liver weights, so detrimental toxic effects were lacking. Histopathological examination revealed that treatment of 5-week old PB/SV40 Tag transgenic rats for 15 weeks with leuprorelin significantly reduced prostate adenocarcinoma progression in the ventral and lateral lobes, whereas complete inhibition was observed in the dorsal lobe in comparison with controls (Table 2). As shown, there are apparent lobe differences; however, the reasons are unknown. Our findings are in good agreement with previously reported studies demonstrating the inhibitory effect of leuprorelin treatment on the growth of the Dunning R 3327 androgen-sensitive rat prostatic tumor transplanted into adult male Copenhagen rats,[13] as well as the growth of male genital organs (testis, seminal vesicles and prostate) in intact Sprague Dawley male rats.[11] Multiple comparison analysis revealed that the action of leuprorelin was not enhanced at the higher dose, which is consistent with previously reported studies of leuprorelin dose dependence.[8,11]

Treatment of transgenic rats with low and high doses of leuprorelin produced a significant decrease in serum total testosterone level, but over 50% testosterone remained, while non-significant changes were recorded in serum LH and FSH levels, suggesting direct inhibitory effects on testicular steroidogenesis rather than indirect action through the pituitary-gonadal axis. These findings correlated well with the lack of any significant change in mRNA expression for LHRH receptors in the pituitaries of treated rats. Earlier animal studies revealed inhibition of testicular steroidogenesis in intact rats following leuprorelin treatment, with a subsequent decrease in the relative weight of rat reproductive organs.[6,14] Probable direct inhibitory effects of the drug on the prostate gland might exist in this transgenic strain, as evidenced by the detection of LHRH receptor mRNA expression in the ventral prostates of control and leuprorelin-treated animals by RT-PCR (data not shown). This possibility clearly warrants further investigation.

It is important to note that prostate cancer development and progression in the prostate adenoma in the TRAMP model as well as in our transgenic model is under the regulation of the androgen-dependent probasin promoter, which directs prostate-specific epithelial expression of the SV40 T antigen, an oncoprotein that interacts with retinoblastoma and p53 tumor-suppressor gene products.[9,15] Immunohistochemical and RT-PCR findings for SV40 Tag oncoprotein expression in the prostates of leuprorelin-treated animals showed a remarkable significant reduction in the ventral as well as dorsolateral lobes. DNA synthesis and proliferation of epithelial cells in neoplastic lesions in the ventral prostates were significantly reduced in leuprorelin-treated rats, as revealed by BrdU immunostaining and morphometric analysis of the percentage of relative epithelial areas. The lack of effects on AR protein expression as well as relative AR mRNA expression in the ventral prostates of leuprorelin-treated transgenic animals could be simply interpreted as reflecting reduction in serum androgen levels above the nadir level that would completely suppress production of ARs. We have already reported the effect of surgical castration on prostate tumor development in transgenic rats. Castration at an early stage induced an immature prostate gland structure and completely suppressed development of any neoplastic lesions, while castration at a late stage, that is, at the age of 20 weeks when adenocarcinomas had already developed, induced marked apoptosis of tumor cells leading to complete disappearance of carcinomas.[9] Compared to the previous data with surgical castration, the present data demonstrate suppression effects of leuprorelin to be rather mild and lobe specific. If suppression of testosterone was largely responsible, such lobe specificity would not be

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Table 3. Representative profile of some downregulated genes (<two-fold with respect to controls) in the ventral prostates of PB/SV40 Tag transgenic rats following treatment with a low leuprorelin dose

Function	GenBank no.	Gene name	Fold change
Apoptosis	NM_012922	Caspase 3 (Casp3)	0.48
	NM_053420	BCL2/adenovirus E1B 19 Kda-interacting protein 3 (Bnip3)	0.47
	NM_134334	Cathepsin D (Ctsd)	0.40
	NM_173114	Prostatic androgen-repressed message-1 (PARM-1)	0.39
	NM_012588	Insulin-like growth factor binding protein 3 (Igfbp3)	0.36
	NM_022277	Caspase 8 (Casp8)	0.33
	NM_031328	B-cell CLL/lymphoma 10 (Bcl10)	0.32
	NM_031735	Serine/threonine kinase 3 (Stk3)	0.31
	NM_017312	Bcl-2-realted ovarian killer protein (Bok)	0.26
	NM_021752	Apoptosis inhibitor (Api2)	0.25
	NM_031700	Claudin 3 (Cldn3)	0.22
	NM_031775	Caspase 6 (Casp6)	0.20
	NM_031098	Rho-associated kinase beta (Rock1)	0.05
Angiogenesis and invasion	NM_133523	Matrix metalloproteinase 3 (MMP3)	0.38
	U68726	Neogenin	0.34
	NM_031055	Matrix metalloproteinase 9 (MMP9)	0.31
	NM_012671	Transforming growth factor alpha (TGFA)	0.27
	NM_022221	Neutrophil collagenase (MMP8)	0.26
	NM_022603	Growth factor binding protein 1 (Fgfbp1)	0.23
	NM_022266	Connective tissue growth factor (Ctgf)	0.20
Cell cycle and growth	NM_171991	Cyclin B1 (Ccnb1)	0.49
	NM_012704	Prostaglandin E receptor 3 (Ptger3)	0.49
	NM_053464	Spermidine synthase (Srm)	0.42
	NM_053677	Protein kinase Chk2 (Rad53)	0.37
	NM_019219	Retinoblastoma-binding protein 9 (Rbbp9)	0.37
	NM_019296	Cell division cycle 2 homolog A (Cdc2a)	0.36
	NM_013015	Prostaglandin D2-synthase (Ptgds)	0.35
	NM_080400	Checkpoint kinase 1 homolog (Chek 1)	0.32
	NM_021740	Prothymosin alpha (Ptma)	0.28
	NM_031094	Retinoblastoma-like 2 (Rbl2)	0.25
	NM_199501	Cyclin dependent kinase 2 (Cdk2)	0.25
	NM_021583	Prostaglandin E synthase (Ptges)	0.25
	NM_052981	Cyclin H (Ccnh)	0.24
	NM_022381	Proliferating cell nuclear antigen (Pcna)	0.17
Cell signaling	NM_177933	Sel1 (Suppressor of lin-12) 1 homolog (Sel1h)	0.49
	NM_017020	Interleukin 6 receptor (Il6r)	0.48
	NM_017071	Insulin receptor (Insr)	0.47
	NM_012747	Signal transducer and activator of transcription 3 (Stat3)	0.46
	NM_130405	Src associated in mitosis (Sam68)	0.46
	NM_022532	v-raf murine sarcoma 3611 viral oncogene homolog 1 (Araf1)	0.45
	L26267	Nuclear factor Kappa B p105 subunit mRNA (NFkB)	0.44
	NM_012514	Breast cancer 1 (Brca1)	0.43
	NM_057211	Kruppel-like factor 9 (Klf9)	0.43
	NM_017218	Avian erythroblastosis oncogene B3 (Erbb3)	0.41
	NM_031514	Janus kinase 2 (Jak2)	0.38
	NM_013145	Guanine nucleotide binding protein, alpha inhibiting 1 (Gnai1)	0.37
	AF231407	Calmodulin III (Calm3)	0.34
	NM_031338	Ca^{++}/calmodulin-dependent protein kinase kinase beta (Cam2KK)	0.32
	NM_017198	p21-activated kinase 1 (Pak1)	0.28
	NM_012499	Adenomatosis polyposis coli (Apc)	0.28
	NM_053777	Mitogen activated protein kinase 8 interacting protein (Mapk8ip)	0.27
	NM_033230	v-akt murine thymoma viral oncogene homolog 1 (Akt1)	0.26
	NM_031143	Diacylglycerol kinase zeta (Dgkz)	0.23
	NM_013022	Rho-associated coiled-coil forming kinase 2 (Rock2)	0.18
	NM_053357	Beta-catenin (Catnb)	0.10
Replication, DNA repair, transcription and translation	NM_053857	Eukaryotic translation initiation factor 4E binding protein 1 (Eif4ebp1)	0.49
	NM_031772	RNA polymerase I (Rpo1–4)	0.45
	NM_171995	Damage-specific DNA binding protein 1 (Ddb1)	0.45
	XM_234239	DNA repair endonuclease	0.44
	NM_012866	Nuclear transcription factor-Y gamma (Nfyc)	0.44
	NM_021662	DNA polymerase delta, catalytic subunit (Pold1)	0.43

Table 3. *continued*

Function	GenBank no.	Gene name	Fold change
	NM_053480	DNA polymerase alpha subunit II (Pola2)	0.42
	NM_031340	Timeless homolog (Timeless)	0.41
	NM_133609	Eukaryotic translation initiation factor2B, subunit 3 (Eif2b3)	0.41
	NM_022397	Ribonucleoprotein F (Hnrpf)	0.39
	NM_138873	Nibrin (Nbn, p95)	0.39
	NM_031058	Mismatch repair protein (Msh2)	0.32
	NM_031107	S6 protein kinase (Rsk-1)	0.30
	NM_031599	Eukaryotic translation initiation factor 2 alpha kinase 3 (Eif2ak3)	0.29
	NM_053528	DNA polymerase gamma (Polg)	0.23
	NM_017141	DNA polymerase beta (Polb)	0.21
	NM_138866	Initiation factor (eIF-2be)	0.17
	AJ011608	DNA polymerase alpha subunit IV primase	0.05
Secretory activity	NM_012836	Carboxypeptidase D (cpd)	0.49
	NM_017284	Proteasome subunit, beta type 2 (Psmb2)	0.48
	NM_022219	Alpha 1,3-fucosyltransferase (Fuc-T)	0.46
	NM_024151	ADP-ribosylation factor 4 (Arf4)	0.41
	NM_053406	Protein O-mannosyltransferase 1 (Pomt1)	0.33
	AF102262	N-acetylglucosamine galactosyltransferase (beta1-4GT)	0.29
	NM_021869	Syntaxin 7 (Stx7)	0.27
	NM_031722	Coated vesicle membrane protein	0.24
	NM_019364	Vesicle transport-related	0.22
Metabolism	NM_012941	Cytochrome P450, subfamily 51 (Cyp51)	0.49
	NM_013134	3-hydroxy-3-methylglutaryl-coenzyme A reductase (Hmgcr)	0.47
	NM_080886	Sterol-C4-methyloxidase-like (Sc4mol)	0.43
	NM_012621	6-phosphofructo-2-kinase/fructose-2,6-biphosphatase 1 (Pfkfb1)	0.36
	NM_053291	Phosphoglycerate kinase 1 (Pgk1)	0.36
	NM_024381	Glycerol kinase (Gyk)	0.33
	NM_031118	Acyl-coenzyme A: cholesterolacyltransferase (Soat1)	0.31
	NM_023104	Acetoacetyl-CoA synthetase	0.31
	NM_017136	Squalene epoxidase (Sqle)	0.30
	NM_030992	Phospholipase D1 (Pld1)	0.28
	NM_012851	Hydroxysteroid 17β-dehydrogenase 1 (Hsd17b1)	0.26
	NM_198738	Phosphoserine aminotransferase 1 (Psat1)	0.21
	NM_172062	Prolyl 4-hydroxylase α subunit (P4ha1)	0.18
	NM_031043	Glycogenin (Gyg)	0.14
	NM_021751	Prominin (Prom)	0.14
Miscellaneous	NM_053946	Implantation-associated protein (IAG2)	0.49
	NM_012548	Endothelin 1 (Edn1)	0.47
	NM_199266	Cystatin related protein 2	0.44
	NM_022391	Pituitary tumor-transforming 1 (Pttg1)	0.43
	NM_022298	Alpha-tubulin (Tuba1)	0.40
	NM_031821	Serum-inducible kinase (Snk)	0.38
	NM_173102	Tubulin, beta (Tubb5)	0.38
	NM_199370	Keratin 8 (Krt8)	0.30
	NM_012715	Adrenomedullin (Adm)	0.17
	NM_175759	Kallikrein, submaxillary gland S3 (rK9, K1k9)	0.15
	NM_012718	Androgen regulated 20 KDa protein (Andpro)	0.08

expected as with surgical castration. Those findings support our speculation that suppression of tumor development in the present work was partly due to specific effects of the LH-RH agonist.

Our results thus suggest that inhibition of prostatic adenocarcinoma development in the ventral, dorsal and lateral prostates of PB/SV40 Tag transgenic rats by leuprorelin treatment was mainly due to downregulation of SV40 Tag oncoprotein expression and partly due to reduction of the serum androgen level. In addition, some androgen-independent mechanisms resulting in reduction of cell proliferation and regression of prostate cancers might be involved. The present microarray analysis indicated that many kinds of genes, including examples involved in apoptosis, angiogenesis, the cell cycle and growth, were influenced by leuprorelin.

In conclusion, the LHRH agonist leuprorelin acts to inhibit prostate carcinogenesis in PB/SV40 Tag transgenic rats by multiple mechanisms including reduction of testosterone biosynthesis, suppression of SV40 Tag oncoprotein expression and alteration in the expression of many genes that are critically involved in the control of cell proliferation and cell cycle progression, transcription and translation, signaling, angiogenesis and invasion, metabolism and cytoskeleton formation. This study also confirmed the suitability of the rat

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Table 4. Representative profile of some overexpressed genes (>two-fold with respect to controls) in the ventral prostates of PB/SV40 Tag transgenic rats following treatment with a low leuprorelin dose

Miscellaneous	NM_053968	Metallothionein 3 (Mt3)	7.66
	NM_012657	Serine protease inhibitor (Spin2b)	6.79
	NM_145774	Rab38, member of RAS oncogene family	3.93
	NM_012774	Glypican 3 (Gpc3)	3.57
	NM_012580	Inhibin alpha (Inha)	3.50
	NM_144737	Flavin-containing monooxygenase 2 (Fmo2)	3.03
	NM_012662	Seminal vesicle protein 4 (Svp4)	2.82
	NM_012789	Dipeptidyl peptidase 4 (Dpp4)	2.74
	NM_024136	Epididymal retinoic acid-binding protein (Erabp)	2.39
	NM_080479	Melanoma antigen, family D, 2 (Maged2)	2.35
	NM_053348	Fetuin beta (Fetub)	2.30
	NM_139104	Estrogen-regulated protein CBL20, 204 KD	2.23
	NM_199119	DEAD (Asp-Glu-Ala-Asp) box polypeptide 24 (Ddx24)	2.09
	NM_012880	Superoxide dismutase 3 (Sod3)	2.04

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