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TITLE: Dietary Influences on Alpha-Methylacyl-CoA Racemase (AMACR) Expression in the Prostate

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14. ABSTRACT Alpha Methyl Acyl CoA Racemase (AMACR), a peroxisomal and mitochondrial enzyme, is up regulated in majority of prostate cancers (PCa). This enzyme is involved in the breakdown of phytanic & pristanic acids, which are derived primarily through the ingestion of dairy and red meat products. There are no studies done so far that have examined the relationship of this enzyme with red meat and dairy intake and therefore PCa risk. The current research focuses on examining the relationships between AMACR expression in the prostate and phytanic/pristanic acid levels in the blood and prostate. So far, ten patients with Pca have been recruited in the study. Research staff has been trained to obtain dietary information as well as process tissue and blood samples from participants. Protocols for processing biological samples have been established. Preliminary optimization of laboratory assays relevant to the study is being performed. The long term goal of this project is to better understand relationships between diet and AMACR expression and its implication in PCa risk. prostate cancer risk.						
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Introduction

Alpha Methyl Acyl coA Racemase (AMACR), a peroxisomal and mitochondrial enzyme, is known to be up regulated in majority of prostate cancers at the protein and mRNA transcript level. This enzyme is involved in the breakdown of phytanic and pristanic acids, which are branched chain fatty acids. These fatty acids cannot be produced de-novo by humans and are derived primarily through the ingestion of dairy and red meat products. Although, epidemiologic studies in the past have shown association between dairy/red meat ingestion and prostate cancer risk, there are no studies done so far that examined the relationship of this enzyme with red meat and dairy intake and therefore prostate cancer risk. The current research focuses on examining the relationships between AMACR expression in the prostate and phytanic/pristanic acid levels in the blood and prostate. We postulate that men with higher intake of red meat and dairy will have higher levels phytanic/pristanic acid in their blood and prostates and consequently have an elevated risk of prostate cancer. Sixty men with prostate cancer will be recruited in this study. Dietary measures for red meat and dairy intake will be evaluated using food frequency questionnaires (FFQ). Phytanic/pristanic acids will be measured in their blood and prostates. In addition, tissue expression for AMACR will be studied at both the protein and RNA level. This study will help us better understand the relationships of dairy/red meat ingestion and prostate cancer risk. It would also help us better understand the exact role of AMACR in prostate carcinogenesis.

Body

The study is currently enrolling participants with prostate cancer from two institutions; the University of Illinois at Chicago (UIC) hospital and the Jesse Brown Veterans Administration Medical Center (JBVAMC). All men with prostate cancer undergoing radical prostatectomy as a treatment are eligible to participate provided they have not received hormonal ablation or neo-adjuvant chemotherapy. Participating subjects have to complete two research visits as a part of this study. A basic schema about patient enrollment is provided in **Figure 1**.

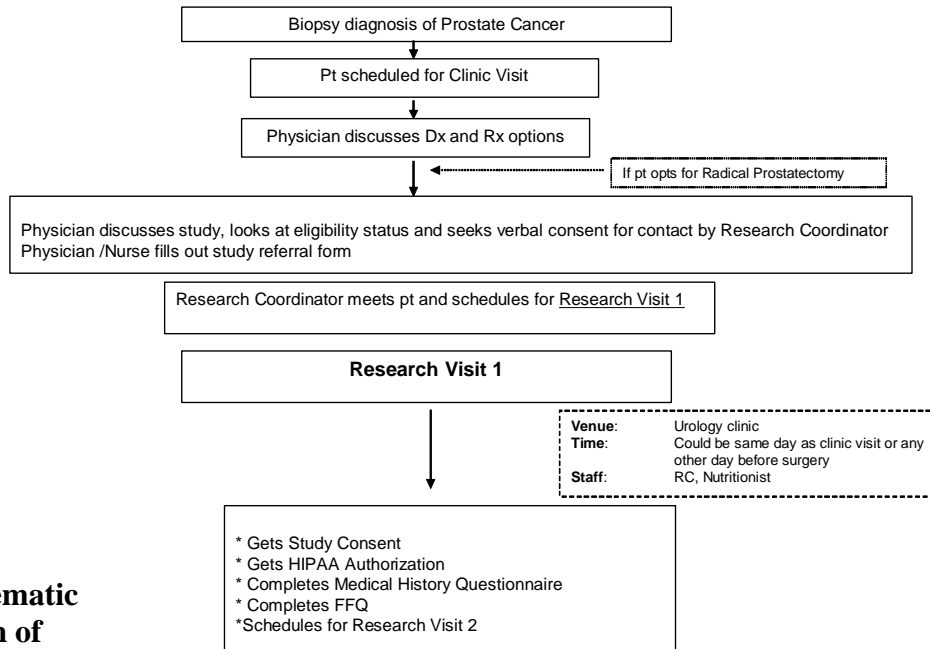
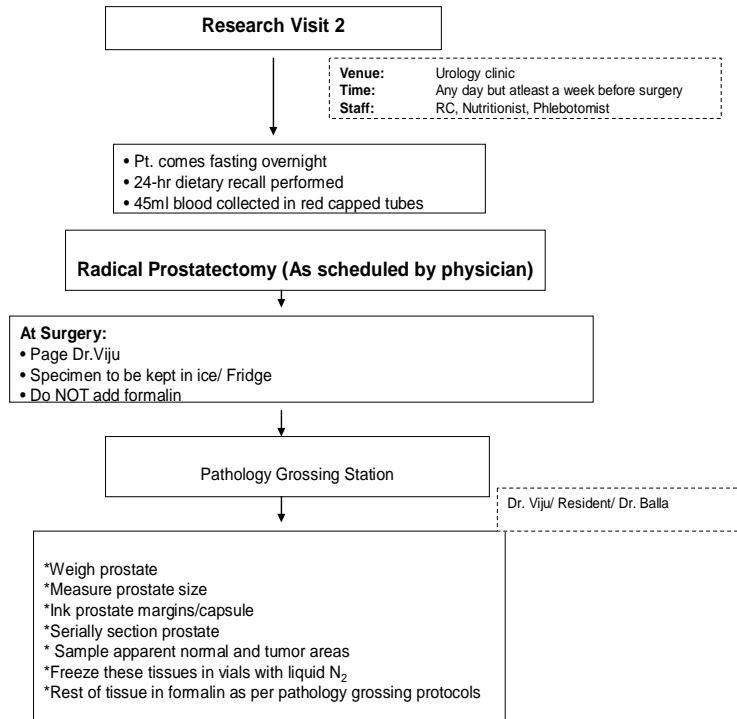


Figure 1. Schematic Representation of Subject Recruitment



Research Activities

We have accomplished the following goals as specified in the statement of work included with the original grant proposal.

Institutional Review Board

Institutional Review Board (IRB) approvals from UIC and JBVAMC have been obtained in addition to the HSRRB approval.

Staff Training

We have a dedicated research coordinator who is fully trained to recruit participants for the study. Staff has also been trained to process samples and data from these subjects. The data includes dietary data in addition to medical data.

Data Management

A Microsoft Access® database has been developed to record participant information. This database is located on a secure server and access to this database is password protected. The database keeps track of patient information, their surgery dates, the research visit dates as well as tracks their tissue and blood samples.

Participant Enrollment

Ten subjects have consented to participate in the study as of date; eight are African American patients while the other two are Caucasian patients. **Table 1** provides information about the recruitment status of these subjects.

Table 1: AMACR Study Recruitment Status

	<i>Number of subjects</i>
Participants who have completed Research visit 1	2
Participants who have completed Research visits 1 & 2	4
Participants who have completed the study	2
Participants who were withdrawn	2
Total consented participants	10

Laboratory Assays

Blood Processing

A protocol for processing blood samples has been developed and is described in detail in the Appendix (Section A). The protocol enables us to separate blood components and store them for future use. In addition, it will enable us to cryopreserve WBCs. Staff members have been trained in blood processing and handling of biohazardous material.

Measurement of Phytanic/Pristanic Acid

Phytanic and pristanic acid are branched chain fatty acids and known substrates for AMACR. These fatty acids will be measured in the serum and prostate using LCMS-MS.

Dr. Richard VanBreemen's laboratory at UIC has developed assays for simultaneous measurement of phytanic and pristanic acid using LCMS-MS. This is an accomplishment due to this project. We are in process of providing de-identified prostate tissue samples and sera for further optimization of the assays.

AMACR Protein Expression

As mentioned in the aims, we intend to study AMACR expression at a protein level using immunohistochemistry and immunofluorescence. Quantification of AMACR can be done manually or using state of the art image analysis systems. As manual scores are semi-quantitative in nature, use of image analysis systems for quantification provides continuous and reproducible measurements especially at lower expression levels. We are developing two novel approaches: one using standard brightfield digital microscopy (ScanScope®, Aperio Corp.) and one using laser scanning cytometry (LSC) with fluorescence (iCys®, CompuCyte) for automated scoring of tissue images.

Scanscope® is a digital bright field microscope with automatic slide scanning properties. There are inbuilt scoring algorithms that can be used to quantify expression of nuclear, cytoplasmic markers. In the past we have shown that biopsies with higher expression of AMACR in their normal glands have a higher risk of a subsequent biopsy being diagnosed with cancer [1]. To validate scoring algorithms, we are currently scanning the same biopsy set using the ScanScope and optimizing algorithms to characterize AMACR expression in normal glands.

Laser Scanning Cytometer (LSC) is a laser based system that is capable of simultaneous acquisition of multiple-fluorescence and brightfield laser-scatter images, from as many as 3 lasers and 5 multiplexed light sensors. The LSC obtains quantitative data using 'Phantom contouring'. Phantoms are round pseudo-objects that are randomly placed on an image and co-localization of various colors within each phantom is recorded and quantified. By staining prostate tissues for both AMACR and Cytokeratin, we can accurately gate out the non-epithelial elements from the image and quantify AMACR expression in the epithelium. More details about quantifying using LSC data can be found in the poster (Appendix –Section B)

AMACR mRNA Expression

As specified in our aims, we will also evaluate AMACR mRNA expression from fresh prostate tissue sampled at the time of grossing. AMACR mRNA will be quantified in both normal and tumor areas sampled. Tumors in the

Figure 2

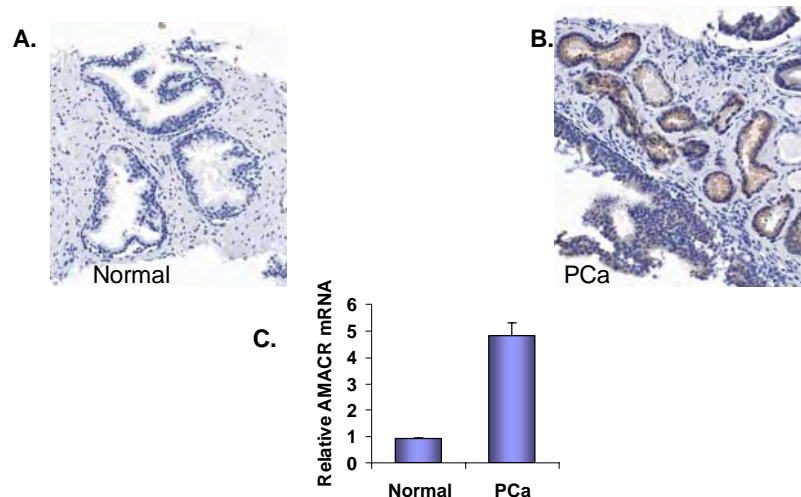


Figure. AMACR mRNA and protein expression in prostate biopsy specimen. Immunohistochemical staining with anti-AMACR in, A, normal and, B, adenocarcinoma in FFPE-prostate biopsy. C. Real-time qRT-PCR analysis of AMACR mRNA expression in macro-dissected normal and PCa epithelium. mRNA levels are shown relative to normal prostate epithelium and normalize to the expression of TBP, B2M and cytokeratin-8. Error represent SEM from two separate experiments (triplicate samples for each).

prostate are difficult to identify grossly and it is possible that the sampled areas may not represent tumor at all. Hence, it is imperative that alternate methods for extracting RNA from formalin fixed paraffin embedded sections are devised.

Dr. Larissa Nonn has developed protocols for RNA extraction on formalin fixed paraffin embedded prostatic biopsies. RNA is first extracted with the RecoverAll™ Total Nucleic Acid Isolation Kit (Ambion Inc., Austin, TX, USA) according to the manufacturer's protocol with the following modifications; protease digestion at 50° C for 4 hours and DNase digestion at 37° C for 1 hour. RNA quality and quantity is measured on the NanoDrop® ND-1000 (NanoDrop Technologies, Wilmington, DE, USA) and RNA is stored in RNA Storage Solution at -80° C. 10 ng of total RNA is the input for the RT reaction. RNA is isolated and mRNA expression analyzed by quantitative reverse-transcription polymerase chain reaction (qRT-PCR)[2] as using RETROscript RT® (Ambion, Austin, TX, USA) and SYBR® Green PCR Master Mix (Applied Biosystems, Foster City, CA, USA). Oligo forward and reverse primers have been designed and optimized for AMACR (5'- agctggccacgatcaact -3', 5'- ggcatacggattctcaccac-3'). Expression will be normalized to four housekeeping genes; TATA-box binding protein (TBP), hypoxanthine phosphoribosyl transferase 1 (HPRT1), beta-actin, and beta-2 microglobulin (B2M). qPCR will be run and analyzed on the Applied Biosystems 7900HT Real-Time PCR System.

We have successfully extracted RNA from macro dissected prostatic biopsies and have demonstrated a significant up regulation of AMACR mRNA in prostate cancer as against normal epithelium (**Figure 2**) consistent with previous reports [3, 4]

Primary Cell Cultures

Protocols for developing primary cell cultures from normal and tumor areas are being developed. We propose to use a small portion of apparently normal and tumor regions sampled at the time of grossing to develop these cell cultures. These cell cultures are different from cell lines by virtue of their limited doublings. Primary cell cultures are valuable *in vitro* model systems to study cancer prevention and treatment strategies. We are in the process of obtaining an IRB approval to develop these cell culture systems.

Key Research Accomplishments

A summary list of key research accomplishments is listed below:

- Procurement of IRB approval
- Establishment of a secure database for subject and sample tracking
- Training of personnel for subject recruitment
- Training of staff for blood and tissue processing
- Preliminary optimization of laboratory assays
- Recruitment of subjects

Reportable Outcomes

- Abstracts - One abstract submitted for presentation at the "Innovative Minds in Prostate Cancer Today - IMPaCT" Meeting
- Presentation – Poster presentation at the Annual 2007 AACR meeting (poster included in the Appendix). Even though the biomarker used for this poster presentation is not directly relevant to the present study, it helped us better understand and optimize the image analysis systems. We are therefore in a better position to evaluate AMACR expression using these systems.

Conclusions

There is a crucial need to identify the biological pathways through which diet affects prostate carcinogenesis. Results of this study could help define important causal links between suspected dietary risk factors for prostate cancer and clinically relevant biomarkers like AMACR. Earlier studies have shown that increased AMACR expression in the normal prostate could be a characteristic of high-risk tissue. If our results confirm a link between diet and AMACR expression, the following inferences will be strengthened: 1) the associations between red meat and dairy intake and prostate cancer risk will be more biologically plausible, leading to the possibility of dietary risk reduction and better identification of high-risk men, and 2) the phytanic/pristanic acid/AMACR pathway will be a more enticing target for discovery of chemopreventive and possibly therapeutic agents. This project could make a number of methodological contributions as well, including the determination as to whether simple food frequency questionnaires or serum samples are capable of predicting tissue levels and whether advanced image analysis techniques provide an important advantage in evaluating pre-malignant changes in tissue.

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Appendix

- **Section A – Blood Processing Protocol**
- **Section B – Poster**
- **Section C – Copies of references**

AMACR Blood Processing Protocol

Collect blood in one 15ml red capped tube and multiple 6ml purple top tubes. Total amount of blood collected will be approximately 45ml.

15ml Red Top – Serum Separation

- First of all, transfer blood from Vacutainer tube to a 15ml corning tube, before the sample clots. (The centrifuge will not close if a 15ml Vacutainer is used)
- Centrifuge at 3000 rpm for 15 min to separate the serum.
- Aliquot the serum into 0.2 ml aliquots
- Label tubes
- Freeze at -80c

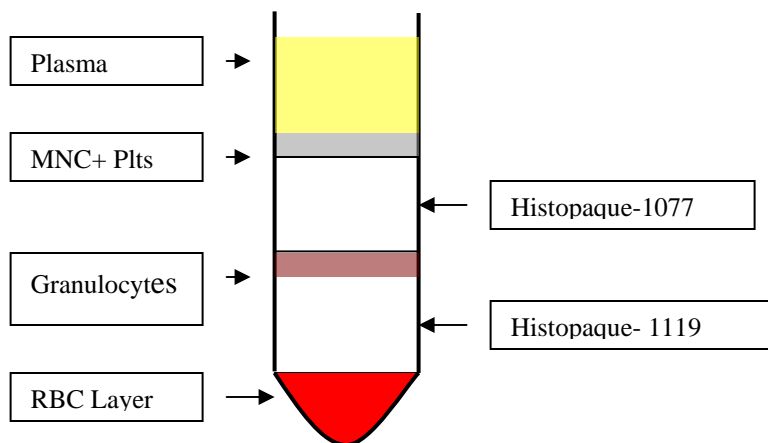
20ml Purple Top (or multiple 6ml purple top tubes) – Plasma, WBC and RBC Separation

- 6ml gets separated for WBC harvesting (described below).
- Transfer the rest into a 15ml corning tube. Centrifuge at 3000 rpm for 15 min to obtain plasma. Separate plasma into four 2ml cryovials.
- Separate the RBCs into another corning tube. Wash multiple times in PBS. Centrifuge at 1200 rpm for 10min. Discard the supernatant and freeze the RBCs into multiple aliquots.

WBC Harvesting

- Sigma Procedure # 1119
- Using a 15ml tube, add 4ml of Histopaque-1119(in the 4° fridge)
- Carefully, layer 4ml of Histopaque-1077 onto Histopaque-1119.
- Carefully layer 6ml of whole blood on top of Histopaque-1077.
- Centrifuge at room temperature at ~2000rpm for 50 minutes.
- Collect the mononuclear cell layer (above Histopaque-1077) and the granulocyte layer (between the 2 Histopaque layers). {First separate them into 2 tubes and mix if there is no RBC contamination. There are chances of RBC contamination when one is trying to get to the PMN layer}.

- Transfer them into one 15ml tube.
- Wash the cells in PBS (bring it to 12-13ml mark) and centrifuge for 10 minutes at 1200rpm.
- Discard the supernatant.
- Resuspend the cells with 9ml of (PBS 0.1mM DFO & 0.1mM DTPA) solution. [To prepare this solution - add 2ul of DFO (500mM) and 2ul (500mM) of DTPA to 10ml of PBS. See pg 3 for DFO and DTPA preparation].
- Centrifuge for 10 minutes at ~1900rpm.
- Discard the supernatant.
- The pellet from the previous step is re suspended in 3ml of freezing mix. Freezing mix is a mixture of 90% Fetal Bovine Serum and 10% DMSO. (i.e 2.7ml of FBS and 0.3ml of DMSO).
- Aliquot into six 0.5ml cryovials.
- Place into RT 'Mr.Freeze' and transfer to -80c. Samples stay at -80c O/N and are subsequently transferred to liquid N2 next day.



Reagents for WBC separation

1. Deferoxamine Mesylate, desferal (DFO) 500mM Stock (500mM DFO)

- Use 1 vial (1gm) of DFO salt (Sigma-D9533)
- Add 3.0 ml of Nuclease free water (Fisher-BP 561-1)
- Filter into sterile tube and store at 4c upto 1-2 months.

2. Diethylenetriaminepentaacetic acid (DTPA) 500mM stock (500 mM DTPA):D6518-10G, DTPA FW =393.35, prepare 10ml of 500mM stock:

Weight [g] =393.35gx0.5Mx0.01L=1.96675g

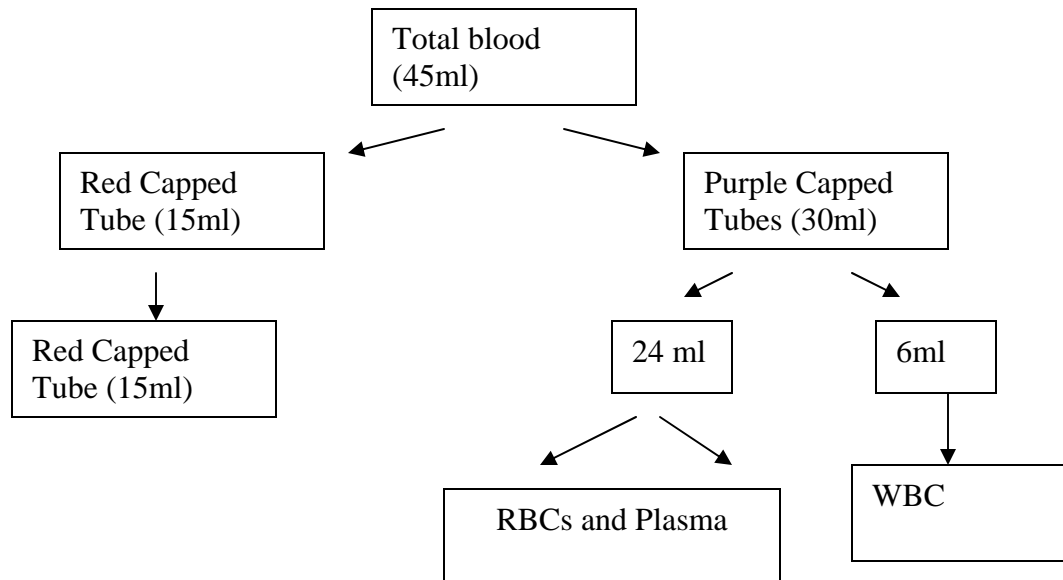
- DTPA 1.96675g
- Nuclease free water ~ 7 ml
- Stir at RT for 1 hr. Check pH. Titrate with 10 N NaOH (dissolve 10.25gm of Sodium hydroxide pellets in 25ml of distilled water). Observe changes of pH. Initial pH=2.27, addition of ~ 2000ul of 10 N NaOH changes ph to7.6. DTPA was completely dissolved. In my case, DTPA was completely dissolved at a much higher pH (8.1).
- Add additional water to make solution to 10ml.
- Filter into sterile tube and store at 4c upto 1-2 months.

3. PBS+ 0.1mM DFO +0.1mM DTPA (PBS-DFO/DTPA)

Prepare fresh 10ml, for complete wash of each sample.

To prepare this solution add 2ul of DFO (500mM) and 2ul (500mM) of DTPA to10ml of PBS.

SUMMARY



Alpha-Methylacyl-CoA Racemase (AMACR) Expression in Normal Prostatic Glands and High- Grade Prostatic Intraepithelial Neoplasia (HGPIN): Association With Diagnosis of Prostate Cancer

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BACKGROUND. Alpha-methylacyl-CoA racemase (AMACR) is strongly expressed in prostate cancer with variable expression in high-grade prostatic intraepithelial neoplasia (HGPIN) and low expression in normal prostate. We examined whether AMACR expression in HGPIN and normal tissue was associated with subsequent diagnosis of cancer or proximity to a cancer focus.

METHODS. Needle core biopsies from 45 patients with isolated HGPIN, 12 radical prostatectomy (RP) specimens with prostatic carcinoma and 6 cystoprostatectomies without prostatic carcinoma were immunostained for AMACR. Among patients with HGPIN, 23 (cases) showed cancer on a later biopsy and 22 (controls) had no cancer with at least 3 consecutive negative biopsies.

RESULTS. In the biopsy set, the mean AMACR expression per gland in the normal compartment of the cases (0.29) was significantly higher than the controls (0.21) ($P = 0.0006$). In the RP set, normal glands near a cancer focus had higher mean AMACR expression than those that were distant ($P = 0.0006$). There was no difference within the HGPIN compartment between cases and controls in the biopsies, or between near and distant glands in the RP set. Mean AMACR staining of normal glands in the cystoprostatectomy specimens was significantly lower than in normal glands in close proximity to a cancer focus.

CONCLUSIONS. Higher expression of AMACR in normal glands near a focus of cancer, as well as in the subjects eventually showing cancer, suggests a possible field effect in prostatic carcinogenesis. AMACR expression in normal glands therefore might be a useful predictor for repeat biopsy outcomes or as an intermediate endpoint in chemoprevention studies. *Prostate* 63: 341–346, 2005. © 2004 Wiley-Liss, Inc.

KEY WORDS: prostatic intraepithelial neoplasia; immunohistochemistry; prostatic neoplasms; alpha-methylacyl-CoA racemase

INTRODUCTION

More than one million prostate biopsies are performed annually in the United States, resulting in the detection of almost 200,000 new cancer cases each year [1]. The high negative biopsy rate results in a sizable population of men with a PSA or digital rectal exam abnormality and at least one negative biopsy. Currently, there are no acceptable methods to stratify these

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patients by risk, and the only logical approach is a sequential follow up with or without a repeat biopsy [2]. If high-risk normal or pre-neoplastic tissue could be characterized at a molecular or cellular level, then these characteristics could be used to predict outcomes of repeat biopsies, and could reduce the morbidity and substantial health care cost associated with serial biopsies. In addition, these same tissue characteristics could be used as intermediate endpoints in Phase 2 chemoprevention trials.

Biomarkers that are differentially expressed in normal, high-grade prostatic intraepithelial neoplasia (HGPIN), and cancer are of particular interest; one recent candidate that has evolved out of subtraction cDNA microarrays is alpha-methylacyl-CoA racemase (AMACR) [3]. AMACR is a peroxisomal and mitochondrial enzyme involved in conversion of branched chain fatty acids and C27-bile acid intermediates to their stereoisomers, which are then diverted towards β oxidation. It has been demonstrated to be consistently over-expressed in a number of cancers and their precursor lesions, particularly in the prostate and colon [4,5]. AMACR is currently used in conjunction with basal cell markers like p63 or 34 β E12 for resolving diagnostically challenging biopsies [6–9]. Although AMACR expression has been widely reported in prostate cancer, not much is known about the significance of inter-individual variation in AMACR in non-cancerous tissues. In this study, we sought to determine if increased AMACR expression in non-cancerous areas on negative biopsy samples is associated with the discovery of cancer on a subsequent biopsy. We also aimed to evaluate if AMACR expression in normal and HGPIN glands near a focus of cancer was different compared to expression in comparable glands that were distant. Lastly, we analyzed AMACR expression in the normal compartment of prostates removed from subjects without prostate cancer (cystoprostatectomies), to compare it to normal tissue from glands known to contain a clinically significant cancer.

MATERIALS AND METHODS

Subjects and Specimens

This study consisted of three sets of paraffin embedded prostatic tissue specimens retrieved from the Northwestern Memorial Hospital repository: a set of 45 prostate biopsies, 12 radical prostatectomies and 6 cystoprostatectomies. All sample sets were collected after Institutional Review Board approval. To test if AMACR expression was associated with subsequent diagnosis of cancer, Bouin's-fixed prostate biopsies from 45 patients with HGPIN but no cancer (i.e., isolated HGPIN) archived from the years 1993 to 1999

and 2002 to 2003 were used. Cases (n=23) were patients with HGPIN who later had a biopsy positive for cancer. Controls (n=22) were patients with HGPIN who had no subsequent diagnosis of prostate cancer and at least three negative biopsies. In both groups, the earliest biopsy diagnosed with HGPIN was used for the study. Both right and left sided biopsies from a subject were included in the study irrespective of the side that showed HGPIN. Hematoxylin and eosin (H/E) stained slides were reviewed to exclude samples where HGPIN could not be confirmed or where prostate cancer might have been present. Glands were considered histologically normal if there was an intact basal cell layer on the H/E section and if there was no evidence of cytological atypia such as crowding, nuclear enlargement, and nucleolar prominence in the luminal cells.

The second set included 12 radical prostatectomy (RP) specimens from 12 prostate cancer patients with Gleason scores 5–9. Eleven subjects had 1 representative block containing all 3 compartments (i.e., normal, HGPIN, and cancer) whereas 1 subject had a block with only cancer and HGPIN compartments. This set was used to see if there was any difference in the AMACR expression between normal glands adjacent to cancer and normal glands distant to cancer.

The third set was comprised of prostates from six cystoprostatectomy specimens removed from patients with bladder cancer. These prostates were examined grossly for suspicious areas, which if present, were submitted for histopathologic examination. Otherwise, a minimum of four random sections were taken. All sections were studied in detail by a pathologist (MRP) to rule out the presence of cancer.

Immunohistochemistry

We noted no difference in the AMACR staining intensity between the Bouin's and formalin fixed control samples and hence followed the same staining protocol for specimens fixed in either fixative. Two adjacent sections were cut from each paraffin block for all specimens. The first section was stained for H/E and the second was immunostained for AMACR. The second section from all the sets was deparaffinized and rehydrated as per routine protocols. Antigen retrieval was carried out in an electric steamer using Target Retrieval Solution (citrate buffer, pH-6, Dako, Carpinteria, CA) for 25 min. Briefly immunostaining was carried out using an autostainer (Dakocytomation, Carpinteria, CA) with a primary rabbit monoclonal antibody for AMACR (Zeta Corp./P504S) in the dilution of 1:100 for ½ hr at room temperature. The sections were then incubated with a ready-to-use anti-rabbit secondary antibody from Dako (EnVision Plus[®]) and color reaction was developed using

TABLE I. Selected Characteristics of Patients With (Cases) and Without (Controls) a Subsequent Diagnosis of Prostate Cancer Following a Biopsy Showing High-Grade Intraepithelial Prostatic Neoplasia (HGPIN)

	Cases	Controls
Number of subjects	23	22
Age, (mean years \pm SD)	64.5 \pm 6.8	65.2 \pm 6.9
Days between HGPIN biopsy and most recent biopsy (mean \pm SD)	291.7 \pm 384.5	504.6 \pm 494.3
Total number of biopsies experienced by subject, (mean \pm SD)	2.7 \pm 0.75	3.7 \pm 0.78

diaminobenzidine (DAB) as the chromagen. The slides were then counterstained with hematoxylin. Suitable positive and negative controls were run in tandem.

Scoring

For the biopsy set, the immunostained slides were mounted with photo-etched cover slips (Bellco Glass, Inc.). These cover slips have 520 alphanumeric squares (grids) etched on them, each measuring 0.6×0.6 mm. At the outset, the grid locations for the HGPIN and normal glands were recorded for each slide in an Excel[®] spreadsheet. All HGPIN glands and normal glands from 10 randomly selected grids were scored per slide. For the RP set, the tumor was initially mapped out on the H/E slide using colored marking pens. Different colors were used to mark out normal and HGPIN areas that were 1, 5, and 10 mm away from tumor. Glands that were in close proximity and within 1 mm distance of the tumor were considered to be "near" and glands that were at least 5 mm distance away were considered to be "distant." These maps were subsequently traced out on the corresponding immunostained slide. Three near and three distant glands for both normal and HGPIN compartments were randomly selected and scored. When available, a gland that was 10 mm from cancer was chosen over a gland that was just 5 mm distant. All scoring was done by a single pathologist (VA) who was not aware of the case/control status of the biopsy samples being examined. Each individual gland was scored on an ordinal scale of 0–3, where 0 was no staining, 1 was weak focal staining, 2 was continuous moderate staining, and 3 was diffuse strong staining. Small acinar proliferation, basal cell hyperplasia, atrophic glands, other benign histological mimics of malignancy, and areas of inflammation were excluded from evaluation and scoring.

To validate the manual scoring methods, digital photomicrographs were taken at $400\times$ magnification from the normal compartment of the biopsy samples

from areas that had been manually scored as 0, 1, 2, or 3 using a Zeiss Axiocam[®]. Five separate images were taken for each scoring level. These images were captured as Tagged Image File Format (tiff) files and were then analyzed using MetaMorph[®] image analysis software (Version 4.6, Universal Imaging Corporation, Philadelphia). First, different color thresholds were established for blue and brown areas using the Hue Saturation and Luminosity (HSL) mode. The same color thresholds were then used for all the images, and a mean gray scale and optical density (OD) index was calculated for each image.

Statistical Analysis

The biopsy, RP, and cystoprostatectomy sample sets were analyzed in two ways: first, mean AMACR scores were calculated per person for each compartment (i.e., normal and HGPIN); second, mean AMACR scores were calculated for glands in a compartment with all subjects combined (mean per gland per compartment). Cases and controls, as well as near and distant areas, were compared by computing means with 95% confidence intervals and *t*-statistics. All statistical analyses were performed using SAS[®] version 8.02 (Cary Institute, NC).

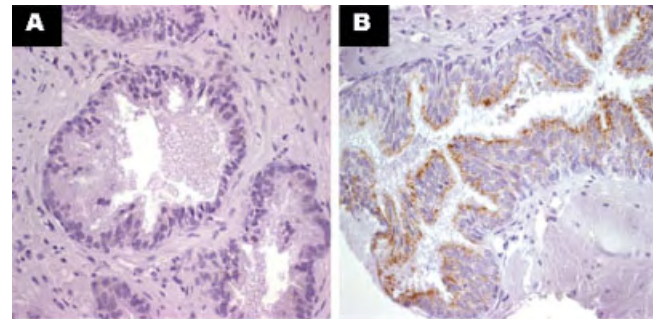


Fig. 1. Normal prostatic gland (A) showing no alpha-methylacyl-CoA racemase (AMACR) staining, and an high-grade prostatic intraepithelial neoplasia (HGPIN) gland (B) with 3+ intensity staining, $400\times$. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

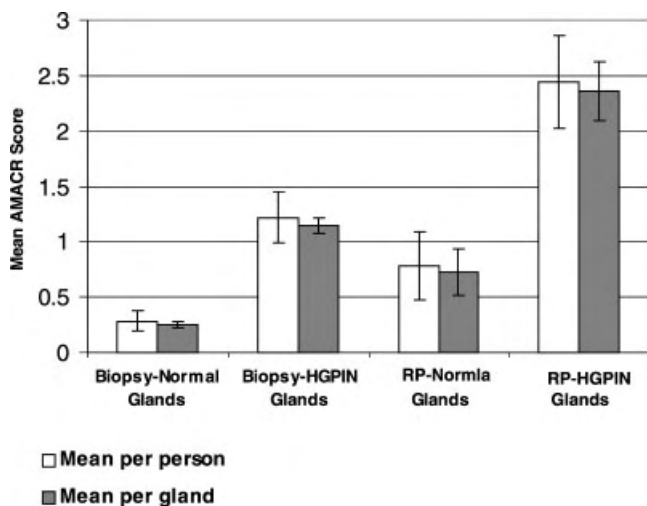


Fig. 2. Mean AMACR score and 95% confidence intervals in the normal and HGPIN compartments for the biopsy and radical prostatectomy (RP) specimens.

RESULTS

AMACR Expression for Cases and Controls in the Biopsy Set

AMACR gave a granular, punctate staining confined to the cytoplasm of epithelial cells with no spill over into the nucleus. There was strong (3+) staining in the positive control slide from a known case of prostate cancer as noted previously [10]. Selected characteristics of patients from the biopsy set are given in Table I. In our biopsy specimens staining in normal glands was negative to weak whereas HGPIN glands stained weak to moderate (Fig. 1). No staining was noted in the stroma or the inflammatory cells. Figure 2 shows that the mean AMACR scores per person and per gland for the HGPIN compartment was significantly higher than the normal compartment. Within the normal compartment, the mean AMACR score per gland for the cases was significantly higher (38% increase) than the controls, as seen in Table II. When data were analyzed as average intensity per person, the difference

in mean AMACR intensity in the normal compartment between cases and controls was greater (62% increase in cases); however, the statistical significance was borderline due to smaller numbers. A difference in mean AMACR intensity in the HGPIN compartment between cases and controls was not observed either on a per subject or a per gland basis. The mean and standard deviation of the OD and gray level scores obtained by MetaMorph[®] compared to the manual scores of 0, 1, 2, and 3 intensity are shown in Table III.

AMACR Expression in RP and Cystoprostatectomy Specimens

As reported previously by others, we found no association between AMACR staining intensity in the cancer compartment in the RP specimens and Gleason scores [11]. Similar to the biopsies, the HGPIN glands showed an overall higher mean AMACR expression per person and per gland when compared to the normal compartment (Fig. 2). For the normal compartment, the mean AMACR score for the near glands per person and per gland was significantly higher than that of the distant glands (Fig. 3, Table IV). There was no difference however, between the near and distant glands for the HGPIN compartment. Mean AMACR staining per person and per gland in the normal compartment of the cystoprostatectomy specimens was significantly lower than that of the normal glands near cancer in the RP set, but was not statistically distinguishable from the distant glands (Table IV).

DISCUSSION

In this study, we demonstrated a significantly higher AMACR expression in normal glands in biopsies from subjects who eventually were discovered to have prostate cancer compared to normal glands from subjects who were not found to have prostate cancer. Furthermore, we observed that AMACR expression in normal glands that were in close proximity to a focus of cancer was significantly higher than the expression in

TABLE II. Alpha-Methylacyl-CoA Racemase (AMACR) Scores in the Normal and HGPIN Tissue Compartments in Biopsy Samples, According to Case-Control Status

Compartment	Status	Score per gland			Score per person		
		n	Mean	95% CI	n	Mean	95% CI
Normal	Cases	804	0.29 ^a	0.26–0.33	23	0.34	0.19–0.50
	Controls	812	0.21	0.17–0.24	21 ^b	0.21	0.11–0.30
HGPIN	Cases	509	1.17	1.08–1.26	23	1.25	0.96–1.55
	Controls	481	1.12	1.03–1.21	22	1.19	0.81–1.56

^aThe mean AMACR score per gland in the normal compartment of the cases was significantly higher than the controls ($P = 0.0006$).

^bOne subject had no glands meeting the criteria for normal in the biopsy.

TABLE III. Mean AMACR Optical Density (OD) and Gray Level Indices by Metamorph[®] Image Analysis in Comparison to Manual Scores in Normal Prostate

Manual scores	Mean OD index \pm SD	Mean gray level index \pm SD
0	0.10 \pm 0.18	134.00 \pm 236.19
1	0.56 \pm 0.48	508.70 \pm 395.65
2	3.60 \pm 2.87	2661.47 \pm 1886.41
3	5.73 \pm 3.86	3895.18 \pm 2215.74

the normal glands that were distant. No such difference in AMACR immunopositivity was, however, observed for the HGPIN compartment. AMACR expression in the HGPIN compartment was quite variable, with a significantly higher intensity of staining than the normal glands, as previously reported [10].

Taken together, these data suggest that up-regulation of this enzyme in the normal glands may precede morphologic evidence of neoplastic transformation. Previous studies have observed AMACR expression in the normal compartment of the prostate. In their study, Leav et al. [12] found AMACR expression in benign hyperplastic glands juxtaposed to carcinoma as well as in carcinomas arising within BPH nodules. In another recent study, Rubin et al. [13] studied AMACR expression using a sensitive immunofluorescence method and found expression of AMACR in low-grade PIN and histologically benign prostate tissue, suggesting the possibility of an early molecular alteration preceding a morphologic alteration. In contrast, Jiang et al. found that 88% of their benign prostates did not show AMACR expression. This group also did not observe increased staining in benign glands adjacent to a cancer focus [11]. The difference between this study

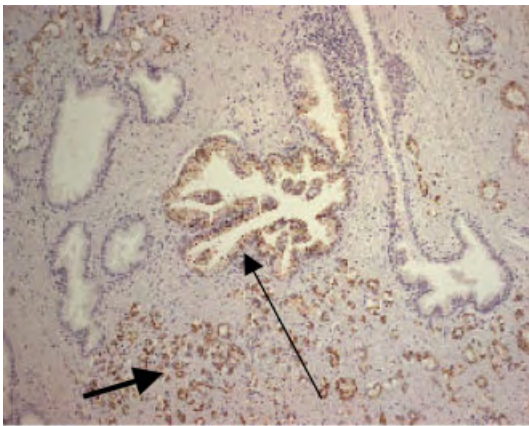


Fig. 3. AMACR staining in a RP specimen: There is increased AMACR expression in the normal gland (normal arrow) adjoining a focus of cancer (bold arrow). [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

and ours could be attributed to use of different antibody sources, staining and scoring methods.

The process of carcinogenesis often involves step-wise progression of molecular events. Events of this nature are represented by the presence of field effects in the adjacent normal tissues [14]. In our study, the presence of AMACR positivity in the normal glands adjoining foci of cancer as well as in the subjects who eventually developed cancer suggests the possibility of a field effect. Indeed, multiple foci of HGPIN have been shown to arise simultaneously within the prostate, lending credibility to the “field effect” hypothesis in prostatic carcinogenesis [15]. Bostwick et al. studied the rates of allelic imbalance at 6 different loci in matched areas of HGPIN and cancer, 21 of the 22 informative cases with allelic imbalance in at least 1 focus of HGPIN and 1 focus of carcinoma showed the same pattern of allelic imbalance in the HGPIN foci and the matched cancer foci. Other biomarkers that have shown higher expression in normal prostatic glands adjoining cancerous foci include pS2, an estrogen inducible protein [16] and EPCA, a nuclear matrix protein [17]. We believe that detection and monitoring of altered expression of such biomarkers in the “field” areas can have prognostic implications and utility as intermediate markers in prevention trials.

Although the results presented here are promising, limitations exist in the study that merit consideration. First, the small size of our study limits power and precludes stratification for confounders like age, number of biopsies, and PSA. However, we looked at the mean AMACR staining in both the compartments of the control group after dichotomizing by age (median age <67 and ≥ 67) and found no difference (data not shown). Limited study size also does not allow for estimation of odds ratios following selection of an appropriate cutoff. Secondly, the retrospective classification of the cases and controls limits perfect determination of cancer free status. However, misclassification of cases as controls would have biased our results towards the null. In the future, we intend to implement a multivariate model comprised of various biomarkers and clinical parameters to study outcomes following negative biopsies in a larger study set. Manual semi-quantitative methods of scoring—though reasonably reproducible—have a limited capacity to make fine distinctions. In this respect, digital image analysis could help in providing a more precise calibration to discriminate between weak and moderate staining.

CONCLUSION

In the search for tissue biomarkers that reliably discriminate normal and cancerous tissues, AMACR is

TABLE IV. AMACR Scores in the Normal and HGPIN Compartments in the Radical Prostatectomy (RP) and Cystoprostatectomy Cases by Their Distance Status

Compartment	Specimen subtypes	Score per gland			Score per person		
		n	Mean	95% CI	n	Mean	95% CI
Normal	Cystoprostatectomy	60	0.52	0.37–0.66	6	0.52	0.19–0.55
	Distant glands	27	0.37	0.18–0.57	9	0.37	0.13–0.61
	Near glands	32	1.03 ^a	0.72–1.34	11	1.01 ^b	0.59–1.44
HGPIN	Distant glands	16	2.06	1.46–2.66	7	2.02	1.21–2.84
	Near glands	31	2.52	2.25–2.78	12	2.35	1.90–2.79

^aP value = 0.0006 for difference in AMACR score per gland between near and distant normal glands.

^bP value = 0.012 for difference in AMACR score per person between near and distant normal glands.

a promising candidate. Our study suggests that increased AMACR expression might be a characteristic of high-risk normal tissue. It does seem plausible that the AMACR gene product, through its role in fatty acid metabolism, may be an important event in the step-wise development of prostate cancer. A similar mechanism might be involved in colon cancer, where increased AMACR expression has also been found and meat-rich diets have been implicated as etiologic factors [5]. In conclusion, we believe that AMACR potentially can be used as an intermediate endpoint in chemoprevention trials or as a risk stratification tool among patients with negative prostatic biopsies.

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Inhibition of p38 by Vitamin D Reduces Interleukin-6 Production in Normal Prostate Cells via Mitogen-Activated Protein Kinase Phosphatase 5: Implications for Prostate Cancer Prevention by Vitamin D

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Abstract

Although numerous studies have implicated vitamin D in preventing prostate cancer, the underlying mechanism(s) remains unclear. Using normal human prostatic epithelial cells, we examined the role of mitogen-activated protein kinase phosphatase 5 (MKP5) in mediating cancer preventive activities of vitamin D. Up-regulation of MKP5 mRNA by 1,25-dihydroxyvitamin-D₃ (1,25D) was dependent on the vitamin D receptor. We also identified a putative positive vitamin D response element within the MKP5 promoter that associated with the vitamin D receptor following 1,25D treatment. MKP5 dephosphorylates/inactivates the stress-activated protein kinase p38. Treatment of prostate cells with 1,25D inhibited p38 phosphorylation, and MKP5 small interfering RNA blocked this effect. Activation of p38 and downstream production of interleukin 6 (IL-6) are proinflammatory. Inflammation and IL-6 overexpression have been implicated in the initiation and progression of prostate cancer. 1,25D pretreatment inhibited both UV- and tumor necrosis factor α -stimulated IL-6 production in normal cells via p38 inhibition. Consistent with inhibition of p38, 1,25D decreased UV-stimulated IL-6 mRNA stabilization. The ability of 1,25D to up-regulate MKP5 was maintained in primary prostatic adenocarcinoma cells but was absent in metastases-derived prostate cancer cell lines. The inability of 1,25D to regulate MKP5 in the metastasis-derived cancer cells suggests there may be selective pressure to eliminate key tumor suppressor functions of vitamin D during cancer progression. These studies reveal MKP5 as a mediator of p38 inactivation and decreased IL-6 expression by 1,25D in primary prostatic cultures of normal and adenocarcinoma cells, implicating decreased prostatic inflammation as a potential mechanism for prostate cancer prevention by 1,25D. (Cancer Res 2006; 66(8): 4516-24)

Introduction

Prostate cancer (PCa) is unique among malignancies in that it generally grows very slowly, likely for decades, before symptoms arise and a diagnosis is finally made. Seemingly, the latency observed in PCa should provide a long window of opportunity for intervention by chemopreventive agents. Laboratory and epidemi-

ologic studies have shown a potential role for vitamin D in the prevention of PCa. Evidence supporting a role for vitamin D in PCa prevention began with studies that linked reduced serum levels of vitamin D metabolites to PCa incidence. Low serum levels of 1,25-dihydroxyvitamin D₃ (1,25D), the active vitamin D metabolite, are associated with increased risk of PCa in older men (1). Decreased serum levels of 25-hydroxyvitamin D₃ (25D), the circulating precursor to 1,25D, also correlate with an increased risk of PCa (1). The latter finding has become more compelling since the discovery that prostate cells are not only sensitive to circulating 1,25D but can also synthesize 1,25D from circulating 25D. Conversion of 25D to active 1,25D by vitamin D 1 α -hydroxylase (1) occurs within the normal prostate and suggests that local production of 1,25D may play a critical role in maintaining normal growth and differentiation.

Studies showing that 1,25D inhibits the growth of primary cultures of prostate cells, established PCa cell lines, and prostate xenograft tumors provide direct evidence for anticancer activity of vitamin D (1). However, mechanisms other than growth inhibition may be responsible for the prevention of PCa by vitamin D.

Using cDNA microarrays, we recently identified a new vitamin D-responsive gene, mitogen-activated protein kinase phosphatase 5 (MKP5; ref. 2). The up-regulation of MKP5, also known as dual-specificity phosphatase 10, was consistently increased by 1,25D treatment of primary cultures of prostatic epithelial cells (2). As a member of the dual-specificity MKP family of proteins that dephosphorylate mitogen-activated protein kinases, MKP5 dephosphorylates p38 and c-jun NH₂-terminal kinase, but not extracellular signal-regulated kinase (3, 4).

The potential ability of vitamin D to inhibit p38 through MKP5 is of interest to PCa prevention because p38 is activated by oxidative stress, hypoxia, and inflammation (5), all of which contribute to PCa development (6, 7). In particular, inflammation plays a causal role in the progression of many cancers including liver, bladder, and gastric cancers (8) and a similar role for inflammation in the development of PCa is now emerging (7). The strongest evidence linking inflammation to PCa is from recent findings that show (a) regular administration of nonsteroidal anti-inflammatory drugs significantly decreases PCa risk in older men by 60 to 80% (9, 10) and (b) men with chronic and/or acute inflammation of the prostate have an increased risk of developing PCa (7, 11).

Inhibitors of p38 are classically anti-inflammatory, suggesting that some of the activities attributed to vitamin D, including PCa prevention, may be a result of p38 inhibition and decreased inflammation. One of the downstream consequences of p38 protein kinase pathway activation is an increase in proinflammatory cytokine production to amplify the inflammatory response (12, 13). Interleukin 6 (IL-6) is a p38-regulated pleiotropic cytokine that has

Note: Supplementary data for this article are available at Cancer Research Online (<http://cancerres.aacrjournals.org/>).

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been historically associated with PCa (14, 15). Elevated levels of IL-6 are found in the serum of PCa patients and primary PCa tumors overexpress IL-6 (14, 16). IL-6 is also involved in the progression of PCa to androgen-independent PCa because it can facilitate androgen receptor signaling in the absence of androgens (15, 17).

Because there is increasing evidence linking inflammation to PCa development, our studies focused on characterizing regulation of IL-6 production via p38 inhibition by 1,25D as a potentially significant cancer prevention activity. Using primary epithelial cell cultures derived from the normal peripheral zone (E-PZ; the major site of origin of prostatic adenocarcinomas; ref. 18) and from primary adenocarcinomas of the prostate (E-CA) as our model system, we characterized MKP5 induction by 1,25D and revealed MKP5 as the mediator of p38 kinase inhibition and decreased IL-6 production by 1,25D. Prostate cancer cell lines derived from metastases, however, have lost the ability to up-regulate MKP5 in response to 1,25D, suggesting selection against this anticancer activity of vitamin D.

Materials and Methods

Cell culture and reagents. Human primary prostatic epithelial and stromal cells were derived from radical prostatectomy specimens. The patients did not have prior chemical, hormonal, or radiation therapy. Histologic characterization and cell culture of the prostate cells was as previously described (19). Epithelial cells (E-PZ and E-CA) were cultured in supplemented MCDB 105 (Sigma-Aldrich, St. Louis, MO) or PFMR-4A as previously described (19). Stromal cells (F-PZ) were cultured in MCDB 105/10% fetal bovine serum (FBS). pRNS1-1 cells are immortalized E-PZ cells (20) and are cultured in keratinocyte serum-free medium (Invitrogen, Carlsbad, CA). Human PCA cell lines LNCaP, PC-3, and DU 145 were acquired from American Type Culture Collection (Manassas, VA). LNCaP cells were cultured in MCDB 105/10% FBS and PC-3 and DU 145 in DMEM (Invitrogen)/10% FBS. Normal human keratinocytes were obtained from Cambrex (East Rutherford, NJ) and cultured according to the instructions of the supplier. Squamous cell carcinoma cell lines SCC-25 and A431 were obtained from Dr. Paul Khavari (Stanford University, Stanford, CA) and cultured in DMEM/10% FBS. All chemicals were obtained from Sigma-Aldrich unless otherwise noted. 1,25-dihydroxyvitamin D₃ (Biomol International, Plymouth Meeting, PA) was reconstituted in 100% ethanol at 10 mmol/L and stored at -20°C.

RNA isolation and quantitative real-time reverse transcription-PCR. RNA was isolated from cells by Trizol (Invitrogen) followed by chloroform extraction. The aqueous phase was then precipitated in 100% isopropanol and the pellet washed in 75% ethanol before resuspension in water. RNA concentration and quality were determined by absorbance ratio at 260/280 nm using a UV spectrophotometer. Total RNA (2 µg) was reverse transcribed using ThermoScript RT (Invitrogen). Resulting cDNA was used for quantitative PCR amplification with gene-specific primers and the DyNAMO SYBR Green kit (Finnzymes, Espoo, Finland) in the Opticon 2 thermocycler (MJ Research, South San Francisco, CA). PCR conditions for all primer sets were optimized and have similar amplification efficiency under the following thermocycler conditions: 95°C 5 minutes, 34 × (95°C 30 seconds, 58°C 30 seconds, 72°C 60 seconds), 72°C 5 minutes. Relative mRNA levels were calculated from the point where each curve crosses the threshold line (Ct) using the following equation: $\text{Rel. value} = 2^{-[\text{Ct}(\text{control}) - \text{Ct}(\text{test})]_{\text{test gene}} / 2^{-[\text{Ct}(\text{control}) - \text{Ct}(\text{test})]_{\text{housekeeping gene}}}$ (21). Reactions were done in triplicate and the values normalized to the expression of the housekeeping gene TATA-box binding protein (*TBP*; ref. 22). Primer sets were *TBP*, 5'-tgctgagaagagtgtgctggag-3' and 5'-tctgaataggctgtggggtc-3'; total MKP5, 5'-atcttgccctctcttct-3' and 5'-attgctgtttgaccttgac-3'; MKP5 isoform 1 specific, 5'-tgaatgtgagtcacatage-3' and 5'-gttagcaggccaggtgtag-3'; MKP5 isoform 2 specific, 5'-tggatgcagctgagattctg-3' and 5'-gttctgctt-gtctgtca-3'; MKP5 isoform 3 specific, 5'-attatgaagtggacttagt-3' and

5'-gttctgcttctgtgctgtca-3'; and CYP24, 5'-ggcaacagtctgggtgaat-3' and 5'-tatttgcggacaatccaaca-3'.

Cell lysate preparation and immunoblot. Cells were lysed in ice-cold 1× Cell Lysis Buffer (Cell Signaling, Beverly, MA) containing 1 µmol/L phenylmethylsulfonyl fluoride and 100 nmol/L okadaic acid. Cells were disrupted by sonication and insoluble cell debris removed by centrifugation at 15,000 × g, 4°C. Protein concentrations of the cell lysates were quantified using the Bio-Rad Protein Dye (Bio-Rad, Hercules, CA). Cell lysates were used fresh or stored at -70°C. Cell lysates (10-30 µg) were mixed with LDS NuPAGE Sample Buffer and separated by electrophoresis through 10% NuPAGE Bis-Tris Gels (Invitrogen) and transferred onto polyvinylidene difluoride membrane. Fresh cell lysates were used for analysis of phosphorylated proteins. Membranes were probed with the following primary antibodies: anti-phospho-p38 rabbit polyclonal and anti-p38 rabbit polyclonal from Cell Signaling, anti-vitamin D receptor (VDR) monoclonal (Santa Cruz Biotechnology, Santa Cruz, CA), and monoclonal anti-actin (Santa Cruz Biotechnology). Following primary antibody incubation overnight at 4°C, the blots were incubated with appropriate secondary horseradish peroxidase-conjugated antibodies (Cell Signaling) and developed with HyGlo enhanced chemiluminescence reagent (Denville Scientific, Metuchen, NJ).

Small interfering RNA transfection. Cells at 75% confluency were transfected with 10 nmol/L of negative control (Ambion, Austin, TX), VDR-specific small interfering RNA (siRNA; Santa Cruz Biotechnology), or MKP5-specific siRNA (Ambion) using siPORT NeoFX (Ambion). Cells were used for experiments after transfection as indicated in results and figure legends.

Chromatin immunoprecipitation. Chromatin immunoprecipitation assays were carried out using Upstate Biologics (Waltham, MA) protocol and reagents. Briefly, cells (1-100-mm dish per treatment) were cross-linked with 1% formaldehyde, harvested, and sonicated before immunoprecipitation. One microgram each of anti-VDR (H-81) and anti-VDR (N-20) rabbit polyclonal antibodies (Santa Cruz Biotechnology) was used for overnight 4°C immunoprecipitation. Protein A-agarose beads were then used to pull down immune complexes. Beads were washed, then reverse cross-linked with NaCl at 65°C. The DNA was extracted with spin columns. PCR (30 cycles) was done on 10% of the recovered DNA using primers flanking the vitamin D response element (VDRE) in the MKP5 promoter; VDRE-MKP5: 5'-ccagagccgagtgcaaatag-3' and 5'-gcaatttctctcagttcc-3'. Primers for the glyceraldehyde-3-phosphate dehydrogenase (GAPDH) promoter (5'-cggctac-tagcggttttacg-3' and 5'-aagaatgcgctgactgt-3') were used as a negative control. PCR products were electrophoresed through 1.5% agarose gels containing 1 µg/mL of ethidium bromide and visualized by UV.

UV irradiation. Prostate cell cultures were exposed to 1,000 J/m² (~45 seconds) of UVB irradiation using calibrated UVB bulbs with a Kodaceal filter. The lid of the cell culture dish and phenol red-containing media were removed during UV irradiation.

In vitro p38 kinase assay. All reagents, antibodies, and protocol for this assay were supplied by Cell Signaling Technologies. Fresh cell lysate was prepared as described above under *Cell lysate preparation and immunoblot*. Cell lysates containing 250 µg of protein were incubated overnight with immobilized phospho-p38 monoclonal antibody to immunoprecipitate activated p38. Bead-immune complexes were washed and resuspended in 1× kinase buffer containing 200 µmol/L ATP and recombinant activating transcription factor-2 (ATF-2) fusion protein as the substrate and incubated at 30°C for 30 minutes to allow phosphorylation of ATF-2. Reactions were terminated by addition of LDS sample buffer. Samples were then heated at 95°C for 5 minutes and kinase activity was determined by immunoblot analysis with phospho-ATF-2 antibody. Input protein (20 µg) was also immunoblotted and probed with anti-p38.

IL-6 ELISA. Prostate cells (10⁷) were plated in 24-well culture plates. After 24 hours, fresh media containing various agents were added (as described in Results and figure legends). Conditioned media were collected following treatment and used at a 2:1 dilution to determine amount of secreted IL-6 with the Human IL-6 ELISA Kit II (BD Biosciences, San Diego, CA). Results were calculated from a standard curve and are expressed as pg/mL IL-6/10⁶ cells or pg/10⁵ cells.

IL-6 promoter activity. A pGL3 luciferase construct containing a 651-bp fragment of the IL-6 promoter and pRL-null-renilla (Promega, Madison, WI) were transiently transfected into E-PZ cells using NeoFX reagent. pGL3-IL-6 was a generous gift from Dr. Oliver Eikelberg at the University of Giessen (Giessen, Germany). Eight hours after transfection, cells were treated with vehicle or 50 nmol/L 1,25D. Cells were UV irradiated 14 hours after vehicle or 1,25D treatment. Luciferase activity was measured 24 hours after UV using the Dual-Luciferase Assay Kit (Promega). The ratio of luciferase to renilla-luciferase was determined to correct for transfection efficiency.

Results

1,25D increases MKP5 mRNA expression in primary cultures of normal prostatic epithelial cells. We previously showed that MKP5 mRNA was increased 3- to 10-fold after 6 hours of treatment with 50 nmol/L of 1,25D in three independent primary cultures of normal human prostatic epithelial cells (E-PZ; ref. 2). The optimal concentration of 1,25D required to up-regulate MKP5 mRNA was determined by quantitative reverse transcription-PCR (RT-PCR). A dose-response curve showed that 1 nmol/L of 1,25D was sufficient to increase MKP5 mRNA in E-PZ cells by 6 hours, but 50 nmol/L of 1,25D was required to maintain MKP5 mRNA up-regulation at 24 hours (Fig. 1A). Higher concentrations of 1,25D are needed at the time points >12 hours because high density E-PZ cells rapidly metabolize and inactivate 1,25D (23). In all subsequent experiments, 50 nmol/L of 1,25D was used to treat subconfluent cultures of E-PZ cells. Upon treatment with 50 nmol/L of 1,25D, increased MKP5 expression was observed as early as 3 hours and maintained for 24 hours in E-PZ cells (Fig. 1B).

The *MKP5* gene is located on chromosome 1 and is transcribed into three distinct mRNA splice variants that putatively encode two different proteins (24). MKP5 splice variant 1 encodes the full-length 52-kDa protein whereas variants 2 and 3 both encode a truncated 16-kDa protein that only contains the dual-specificity phosphatase domain (Fig. 1D). Because the biological significance of the MKP5 splice variants has not yet been characterized, we examined the ability of 1,25D to regulate the mRNA expression of the three MKP5 splice variants by quantitative RT-PCR. All of the

MKP5 mRNA splice variants were induced following 6 hours of treatment with 50 nmol/L of 1,25D, but splice variant 1 seemed to be most abundant and achieved the highest level of mRNA induction in the E-PZ cells (Fig. 1C). Primers within exons 3 to 5 of MKP5, the conserved region present in all MKP5 mRNAs, were used for all subsequent experiments.

Up-regulation of MKP5 mRNA by 1,25D is VDR dependent and MKP5 promoter contains a putative VDRE that associates with VDR on 1,25D treatment. The rapid induction of MKP5 mRNA by 1,25D suggested that MKP5 is a direct target of 1,25D. Direct targets of 1,25D contain one or more VDREs in the promoter region, which mediate transcriptional regulation by VDR binding. Knockdown of VDR levels by VDR siRNA in E-PZ cells abolished the induction of MKP5 by 1,25D (Fig. 2A), showing that induction of MKP5 by 1,25D is VDR dependent. The mRNA expression of vitamin D 24-hydroxylase (CYP24), a well-characterized target of 1,25D, was similarly suppressed in cells transfected with VDR siRNA (Fig. 2A) whereas the expression of *TBP*, a housekeeping gene, was not affected by VDR siRNA transfection. On sequence analysis, a putative VDRE was identified -1,320 bp upstream of the 5' untranslated region in the MKP5 promoter (Fig. 2B). The putative MKP5-VDRE was highly similar to the characterized VDREs present in the promoters of CYP24 and parathyroid hormone-related protein. Chromatin immunoprecipitation assay showed an increased interaction between VDR and the putative MKP5-VDRE that exhibited time-dependent changes on stimulation with 50 nmol/L of 1,25D in E-PZ cells (Fig. 2C). The cyclic nature of VDR interaction with the MKP5 promoter observed in the chromatin immunoprecipitation experiments is consistent with previously described interactions of nuclear hormone receptors with DNA (25). The siRNA and chromatin immunoprecipitation data together provide strong support that MKP5 is directly regulated by 1,25D at the transcription level.

MKP5-mediated p38 inactivation by 1,25D occurs in E-PZ cells and not in PCa cell lines. Phosphorylation of p38 is required for activation of p38 kinase activity. MKP5 dephosphorylates p38, thus reducing p38 kinase activity. Vitamin D has been shown to

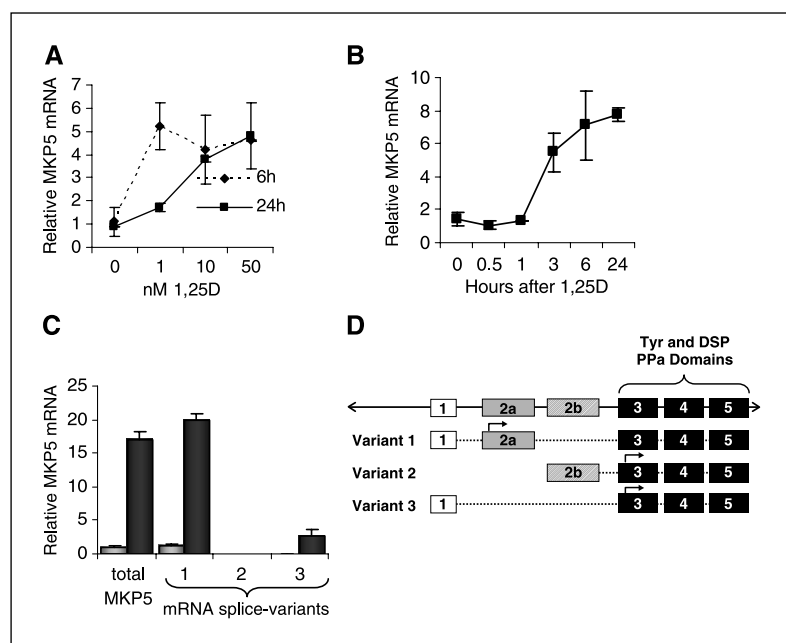


Figure 1. 1,25D increases MKP5 mRNA expression in primary cultures of normal prostatic epithelial cells (E-PZ). Quantitative RT-PCR measurement of MKP5 mRNA levels in E-PZ cells, 6 hours (dashed line) and 24 hours (solid line) after treatment with 1, 10, and 50 nmol/L 1,25D (A) and 0.5, 1, 3, 6 and 24 hours following 50 nmol/L 1,25D treatment (B). C, quantitative RT-PCR analysis of MKP5 mRNA splice variants in E-PZ cells after 6-hour vehicle (light columns) or 50 nmol/L 1,25D (dark columns) treatment (mRNA levels for isoform 2 treated with vehicle and 1,25D are 0.003 ± 0.0007 and 0.014 ± 0.0004 , respectively, but are not visible on this graph). D, diagram of MKP5 mRNA splice variants. Quantitative RT-PCR results are shown relative to untreated control and normalized to expression of housekeeping gene *TBP*. Each experiment was run in triplicate and graphs are representative of two or more separate experiments with different patient-derived E-PZ cells. Bars, SD.

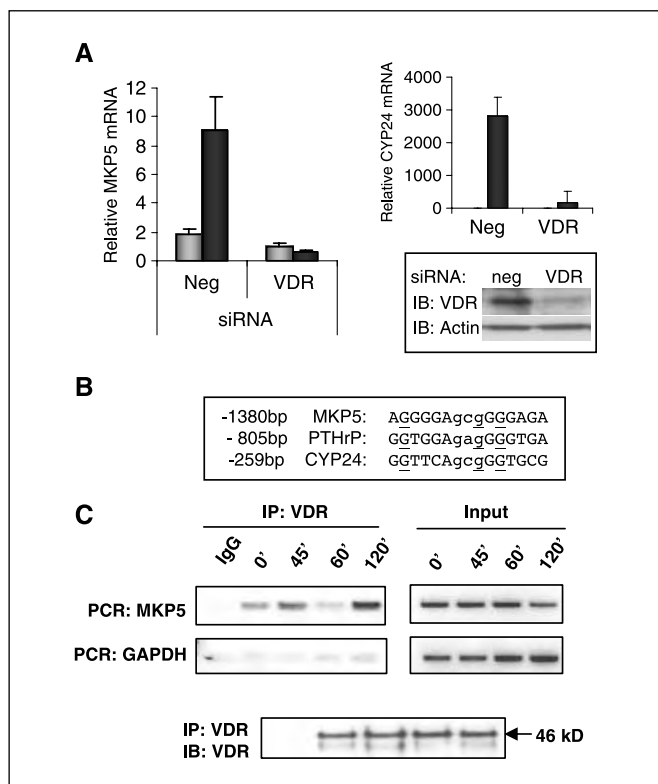


Figure 2. Up-regulation of MKP5 mRNA by 1,25D is VDR dependent and MKP5 promoter contains a putative VDRE that associates with VDR on 1,25D treatment. **A**, quantitative RT-PCR analysis of MKP5 mRNA 6 hours after treatment with vehicle (light columns) or 50 nmol/L 1,25D (dark columns) in E-PZ cells that were transfected for 24 hours with negative control siRNA or VDR siRNA. CYP24 gene expression was included as positive control for VDR knockdown (untreated mRNA level of CYP24 is equal to one and is not visible on this graph) and immunoblot of nuclear lysate (10 μ g) verified VDR knockdown by the siRNA. **B**, diagram of putative VDRE located -1,380 bp of 5'UTR in MKP5 promoter aligned with validated VDREs in parathyroid hormone-related protein and CYP24. **C**, chromatin immunoprecipitation analysis and PCR of putative VDRE in MKP5 promoter and GAPDH promoter following 50 nmol/L 1,25D treatment using rabbit polyclonal VDR antibody for pulldown. Immunoblot of protein precipitate probed with mouse monoclonal VDR antibody shows specific pulldown of VDR. Results are representative of four or more separate experiments with different patient-derived E-PZ cells. Quantitative RT-PCR results are shown relative to untreated control and normalized to expression of housekeeping gene *TBP*. Each experiment was run in triplicate and graphs were representative of two or more separate experiments. Bars, SD.

inhibit osmotic stress-stimulated p38 phosphorylation in keratinocytes (26). We observed a similar inhibition of p38 phosphorylation by 1,25D in E-PZ cells (Fig. 3A). E-PZ cells were pretreated with 1,25D for 14 hours to allow for sufficient up-regulation of MKP5 protein. MKP5 protein levels could not be directly monitored in this study due to lack of an appropriate antibody. After pretreatment with 1,25D, osmotic stress-stimulated phosphorylated p38 levels were appreciably decreased compared with levels in cells not treated with 1,25D. Transfection with MKP5-specific siRNA attenuated induction of MKP5 mRNA by 1,25D compared with negative control siRNA (Fig. 3B) and abolished the suppression of p38 phosphorylation by 1,25D (Fig. 3A), implicating MKP5 as the mediator of p38 inactivation by 1,25D.

We examined the effect of 1,25D on MKP5 in various other prostate-derived cells in comparison with the primary cultures of E-PZ cells. The results showed that, like E-PZ cells, pRNS-1-1 cells also induce MKP5 (Fig. 3C). In contrast, prostate stromal cells (F-PZ) and established PCa cell lines (PC-3, LNCaP, and DU 145)

did not up-regulate MKP5 mRNA following 1,25D treatment (Fig. 3C). pRNS-1-1 cells were generated by SV40 transformation and immortalization of E-PZ cells and are not growth inhibited by 1,25D, although they retain VDR and other responses to 1,25D (1). Prostatic stromal cells too express VDR and show certain responses to 1,25D despite lack of induction of MKP-5 in these cells by 1,25D (1). The PCa cell lines PC-3, LNCaP, and DU 145 all express VDR and respond to 1,25D in other ways (1). Immunoblot analysis showed that in DU 145, PC-3, and LNCaP cells, 1,25D pretreatment did not alter NaCl-induced p38 phosphorylation (Fig. 3D). These data suggest that MKP5 may specifically mediate 1,25D activity in normal prostate cells and that this activity is lost in advanced PCa.

We suspect that MKP5 up-regulation by 1,25D is not unique to prostatic epithelium. Because inactivation of p38 by 1,25D was reported in keratinocytes, we examined the expression of MKP5 in these cells. Similarly to prostatic epithelial cells, normal human keratinocytes showed up-regulation of MKP5 mRNA on treatment with 1,25D, suggesting that MKP5 may mediate p38 inactivation in keratinocytes as well (Supplementary Fig. S1A). Similarly to the PCa cell lines, up-regulation of MKP5 by 1,25D was attenuated in the human squamous cell carcinoma cell lines A431 and SCC-25 (Supplementary Fig. S1B).

MKP5 mediates decreased IL-6 production in E-PZ cells by 1,25D. Published studies have shown that 1,25D inhibits UV-induced IL-6 production in keratinocytes; however, no mechanism has been proposed (27). IL-6 overexpression has been strongly associated with PCa progression and, therefore, inhibition of IL-6 may play an important role in PCa prevention. Because IL-6 induction is downstream of p38 activation and often dependent on p38 activation (13, 28), we tested the role of MKP5 in regulating IL-6 expression in E-PZ cells. An *in vitro* p38 kinase activity assay, using ATF-2 as the substrate, showed that 1,25D pretreatment decreased basal and UV-stimulated p38 activity in E-PZ cells (Fig. 4A). The 1,000 J/m² dose of UVB irradiation used in these experiments did not induce apoptosis or necrosis in E-PZ cells (data not shown). Consistent with p38 inactivation, secreted levels of IL-6 protein following UV treatment were suppressed by 1,25D pretreatment (Fig. 4B). SB202190, a specific p38 inhibitor, similarly decreased UV-stimulated IL-6 production (Fig. 4B). A decrease in IL-6 mRNA expression was observed in 1,25D pretreated samples and this decrease was blocked by transient transfection with MKP5 siRNA (Fig. 4C). The primary mechanism for increased IL-6 production following p38 activation is through IL-6 mRNA stabilization rather than increased mRNA transcription (29). To determine if this is also true for 1,25D regulation of IL-6 mRNA, we examined the effect of 1,25D on IL-6 promoter activity in the absence or presence of UV irradiation. We found that neither UV irradiation nor 1,25D treatment significantly altered IL-6 promoter activity as determined by luciferase assay in E-PZ cells (Fig. 4D1), suggesting that 1,25D is not altering mRNA transcription. When 1 μ mol/L of actinomycin D was used to inhibit new mRNA transcription, we observed that UV irradiation caused IL-6 mRNA stabilization and 1,25D pretreatment decreased the UV-induced IL-6 mRNA stabilization (Fig. 4D2). Under basal conditions, IL-6 mRNA half-life was <45 minutes in E-PZ cells. In UV-irradiated cells, IL-6 mRNA half-life increased to >90 minutes whereas UV irradiation did not significantly alter IL-6 mRNA half-life in 1,25D pretreated cells (Fig. 4D2).

1,25D inhibits tumor necrosis factor α -stimulated p38 activation and IL-6 production. The ability of 1,25D to inhibit

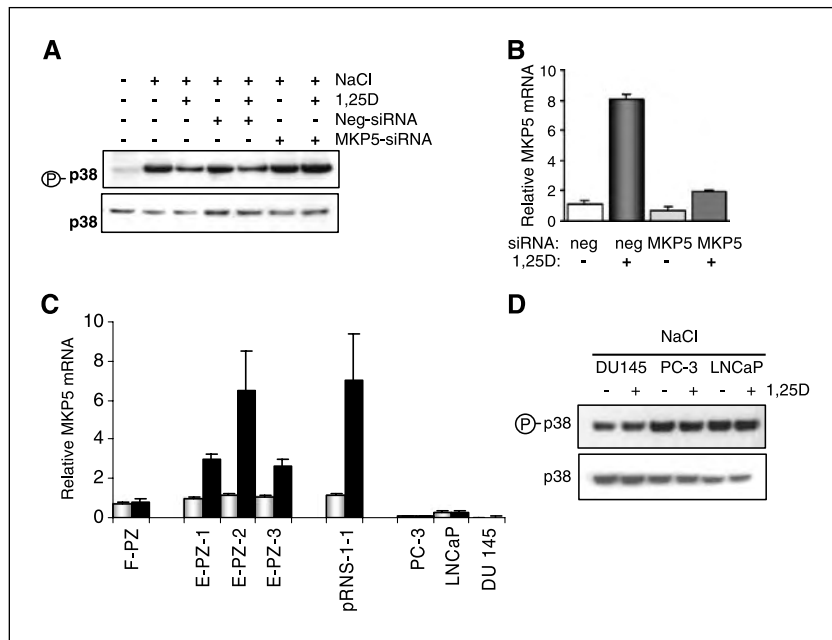


Figure 3. MKP5-mediated p38 inactivation by 1,25D occurs in E-PZ cells and not in PCa cell lines. **A**, immunoblot analysis of p38 phosphorylation in 20 μ g of E-PZ cell lysate 20 minutes after treatment with 0.5 mol/L NaCl. Before NaCl treatment, E-PZ cells were transfected with negative control or MKP5 siRNA for 4 hours, then treated with vehicle or 50 nmol/L 1,25D for 14 hours. **B**, quantitative RT-PCR analysis of MKP5 mRNA expression in E-PZ cells transfected with negative control siRNA (*open columns*) or MKP5 siRNA (*striped columns*) 4 hours before vehicle (*light columns*) or 1,25D (*shaded columns*) treatment for 12 hours. Representative of at least three separate experiments with different patient-derived E-PZ cells. Results are displayed relative to negative siRNA control and normalized to expression of the housekeeping gene *TBP*. **Bars**, SD of triplicate samples. **C**, quantitative RT-PCR analysis of MKP5 mRNA 6 hours after treatment with vehicle (*light columns*) or 50 nmol/L 1,25D (*dark columns*) in primary cultures of prostate stroma (F-PZ) in three different cultures of normal primary prostatic epithelial cells (derived from normal peripheral zone designated E-PZ) and in prostate cell lines pRNS-1-1, LNCaP, PC-3, and DU 145. Quantitative RT-PCR results are displayed relative to control and normalized to expression of the housekeeping gene *TBP*. **Bars**, SD. **D**, immunoblot analysis of p38 phosphorylation 20 minutes after treatment with 0.5 mol/L NaCl in DU 145, PC-3, and LNCaP cells pretreated for 14 hours with vehicle or 50 nmol/L 1,25D.

p38 phosphorylation was further investigated using a more physiologic stress, tumor necrosis factor α (TNF- α). TNF- α is a proinflammatory cytokine released by inflammatory cells that can trigger cell proliferation, necrosis, apoptosis, and induction of other cytokines (12). Interestingly, elevated serum levels of TNF- α are associated with aggressive pathology and decreased survival of PCa

patients (16). In E-PZ cells, TNF- α does not induce apoptosis but does significantly slow cell growth (30). TNF- α binds cell-surface receptors which signal through multiple pathways, including p38 kinase, to increase production of IL-6 and other cytokines (12). Immunoblot analysis showed that TNF- α -stimulated p38 phosphorylation was attenuated by 1,25D pretreatment, similar to the

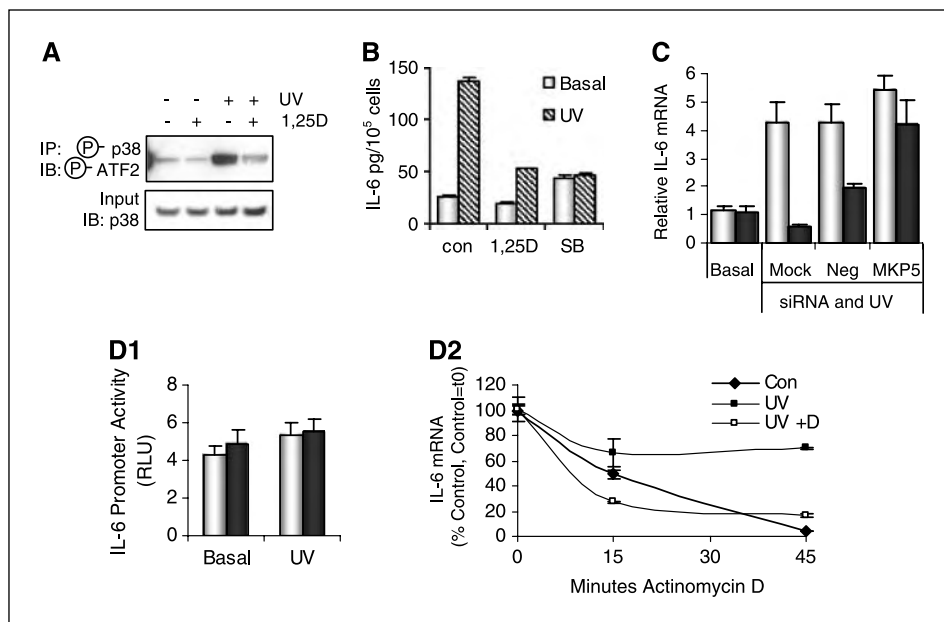


Figure 4. MKP5 mediates decreased IL-6 production in E-PZ cells by 1,25D. **A**, *in vitro* p38 kinase activity assay, using ATF-2 as a substrate, in E-PZ cells 20 minutes after 1,000 J/m² UVB irradiation in E-PZ cells pretreated 14 hours with vehicle or 50 nmol/L 1,25D. **B**, ELISA measurement of secreted IL-6 in cell culture media 24 hours after UVB irradiation (*hatched columns*) in E-PZ cells pretreated with vehicle, 50 nmol/L 1,25D for 14 hours, or 1 μ mol/L SB202190 for 1 hour. **C**, quantitative RT-PCR measurement of IL-6 mRNA in E-PZ cells 24 hours after UV irradiation. Cells were either transiently transfected with negative siRNA or MKP5 siRNA for 4 hours, then pretreated for 14 hours with either vehicle (*light columns*) or 50 nmol/L 1,25D (*dark columns*) before UV. **D1**, luciferase activity of pGL3-IL-6 24 hours after UV irradiation in E-PZ cells pretreated for 14 hours with vehicle (*light columns*) or 50 nmol/L 1,25D (*dark columns*). **D2**, quantitative RT-PCR analysis of IL-6 mRNA stability in E-PZ cells following UV irradiation. Cells were treated with 1 μ mol/L actinomycin D for 0, 15, and 45 minutes. Actinomycin was dosed 30 minutes after UV and cells were pretreated 14 hours before UV with vehicle (\blacksquare) or 50 nmol/L 1,25D (\square). IL-6 mRNA levels under basal conditions after 15 to 45 minutes of treatment with 1 μ mol/L actinomycin D were shown as control (\blacklozenge).

effect of 1,25D on UV-stimulated p38 phosphorylation in E-PZ cells (Fig. 5A). Changes in IL-6 mRNA and secreted protein levels were followed over a time course after TNF- α stimulation and showed that 1,25D pretreatment attenuated the initial production of IL-6 and completely inhibited the accumulation of IL-6 in the media (Fig. 5B and C).

1,25D up-regulates MKP5 mRNA and inhibits TNF- α -stimulated IL-6 production in matched pairs of normal and tumor cells from individual PCa patients. Because we observed a difference in regulation of MKP5 by 1,25D between E-PZ cells and PCa cell lines, we analyzed the effect of 1,25D on MKP5 and IL-6 in matched pairs of normal (E-PZ) and tumor (E-CA) cells from two PCa patients with localized Gleason grade 4/3 cancers (individuals A and B). Quantitative RT-PCR analysis showed that MKP5 mRNA was up-regulated by 1,25D in E-CA as well as E-PZ cells from both individuals (Fig. 6A). In addition, IL-6 mRNA and protein levels, following TNF- α stimulation, were decreased by 1,25D pretreatment in all of the matched pairs of normal and cancer cultures (Fig. 6B and C). Although patient-to-patient variability was evident

in the extent of TNF- α -stimulated IL-6 production, cancer cells from primary adenocarcinomas retain the ability to up-regulate MKP5 in response to 1,25D, in contrast to the established metastases-derived cell lines (DU 145, LNCaP, and PC-3).

Discussion

The purpose of these studies was to explore the potential significance of MKP5 in mediating PCa prevention by vitamin D. We previously identified MKP5 as a target of 1,25D in normal human prostatic epithelial cells by microarray analysis (2). The results of our studies suggest that the ability of vitamin D to inhibit p38 signaling, via MKP5 up-regulation, may be a significant antitumor activity of vitamin D (Fig. 7).

MKP5 is likely a direct target of 1,25D, regulated by a positive VDRE in the promoter region of the gene. Treatment of E-PZ cells with 1,25D produced a time- and dose-dependent increase in MKP5 mRNA that was dependent on VDR expression. Furthermore, VDR was found to associate with the VDRE in the MKP5 promoter on 1,25D treatment. These data support direct transcriptional activation of the *MKP5* gene by 1,25D. Consistent with increased levels of MKP5, 1,25D inhibited p38 phosphorylation. MKP5 siRNA blocked p38 inactivation by 1,25D, which further showed that MKP5 mediates p38 inactivation by 1,25D.

The ability of 1,25D to inactivate p38 led us to examine the regulation of IL-6, which is downstream of p38 activation (28), by 1,25D. Suppression of UV-stimulated IL-6 production by 1,25D was previously shown in keratinocytes (27) and we suspected that similar activity could be mediated by MKP5 in normal prostatic epithelial cells. Using MKP5 siRNA, we showed that 1,25D inhibited UV-stimulated p38 activity and IL-6 production in a MKP5-dependent manner in E-PZ cells. UV irradiation did not increase IL-6 promoter activity but did increase mRNA half-life, indicating posttranscriptional regulation of IL-6 mRNA expression. 1,25D pretreatment was able to attenuate the UV-stimulated increase in IL-6 mRNA half-life. Induction of IL-6 by a more physiologically relevant stress, TNF- α , was similarly inhibited by 1,25D.

IL-6 has been shown to be negatively regulated by androgens and the androgen receptor in murine bone marrow-derived fibroblasts (31). It is unlikely that androgen receptor contributes to IL-6 regulation observed in E-PZ cells because E-PZ cells are typical of prostatic basal epithelial cells and do not express androgen receptor (32). There is evidence of cross-talk and regulation of androgen receptor by vitamin D (1). In cells where androgen receptor and VDR are both expressed, such as the luminal cells of the prostate, it is possible that cooperation of the two pathways could facilitate a further decrease in IL-6 expression.

IL-6, as well as other interleukins and/or their receptors, are overexpressed in PCa tissue and/or serum of PCa patients (15, 33). Elevated serum levels of IL-6 and TNF- α are associated with aggressive pathology and decreased survival of PCa patients (16). Increased IL-6 staining is observed in malignant prostate tissue compared with adjacent normal tissue and IL-6 also contributes to the development of hormone-refractory cancer by androgen-independent activation of the androgen receptor (17). *In vitro*, the PCa cell lines DU 145, PC-3, and LNCaP all express the IL-6 receptor and are responsive to exogenous IL-6; however, DU 145 and PC-3 also greatly overexpress endogenous IL-6 whereas the LNCaP cell line does not express any IL-6 (15). The mechanism(s) leading to constitutive overexpression of IL-6 in PCa cells and

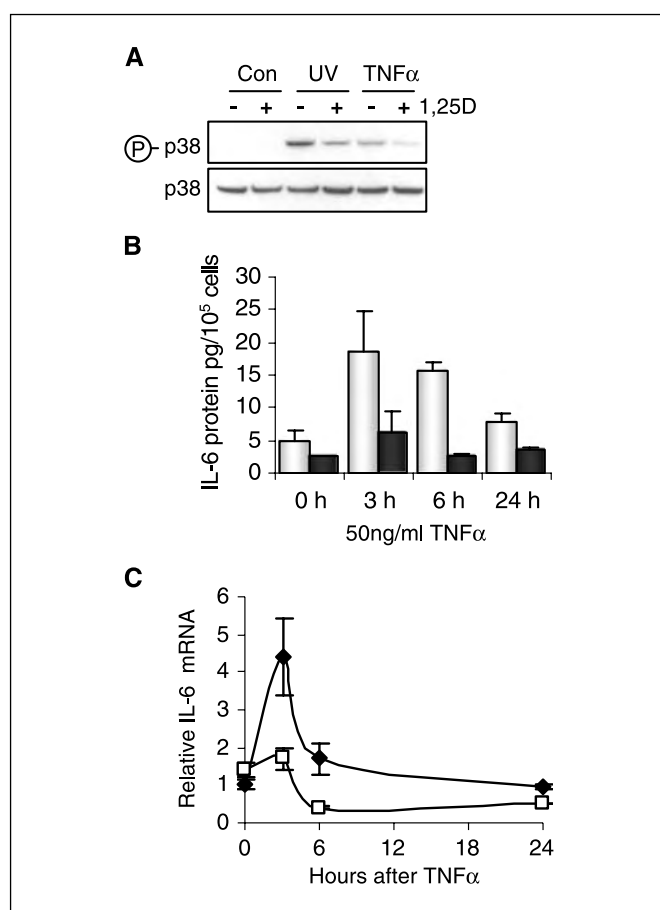


Figure 5. 1,25D inhibits TNF- α -stimulated p38 phosphorylation and IL-6 production. **A**, immunoblot analysis of p38 phosphorylation 20 minutes after treatment with 1,000 J/m² UVB or 50 ng/mL TNF- α in E-PZ cells pretreated 14 hours with vehicle or 50 nmol/L 1,25D. **B**, ELISA measurement of secreted IL-6 in cell culture media 3, 6, and 24 hours after 50 ng/mL TNF- α in E-PZ cells pretreated 14 hours with vehicle (light columns) or 50 nmol/L 1,25D (dark columns). **C**, quantitative RT-PCR analysis of IL-6 mRNA 3, 6, and 24 hours after 50 ng/mL TNF- α in E-PZ cells pretreated for 24 hours with vehicle (◆) or 50 nmol/L 1,25D (□). IL-6 gene expression relative to untreated control and normalized to expression of the housekeeping gene *TBP*. Bars, SD of triplicate samples.

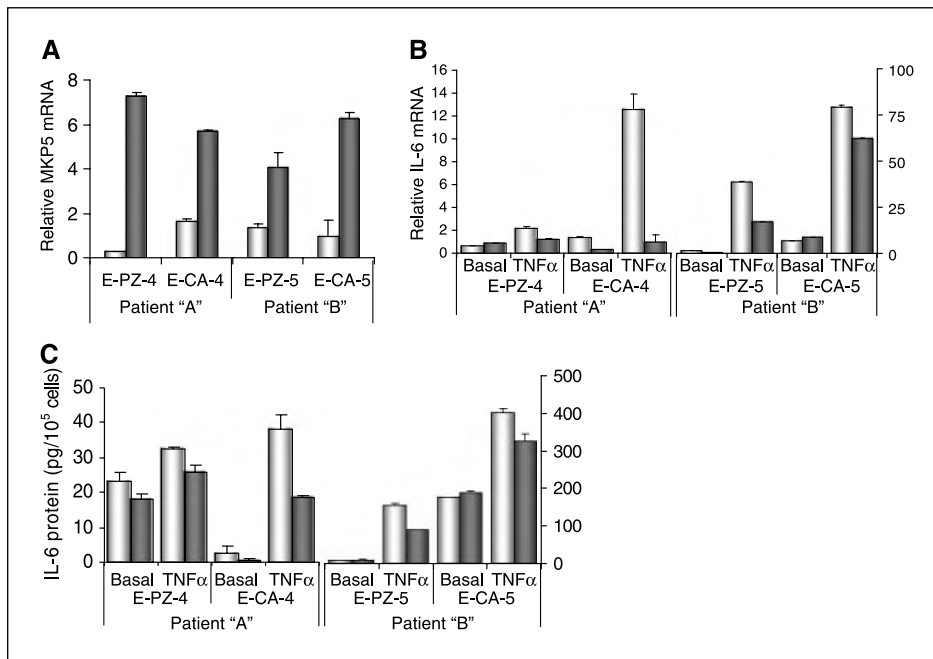


Figure 6. 1,25D up-regulates MKP5 mRNA and inhibits TNF- α -stimulated IL-6 production in matched pairs of normal and tumor cells from individual PCa patients. **A**, quantitative RT-PCR measurement of MKP5 mRNA levels in patient **A** E-PZ and E-CA cells and patient **B** E-PZ and E-CA cells 15 hours after treatment with vehicle (open columns) or 50 nmol/L 1,25D (shaded columns). **B**, quantitative RT-PCR analysis of IL-6 mRNA 3 hours after 50 ng/mL TNF- α in cells pretreated 15 hours with vehicle (open columns) or 50 nmol/L 1,25D (shaded columns). MKP5 and IL-6 gene expressions are shown relative to untreated control and normalized to expression of the housekeeping gene *TBP*. Bars, SD of triplicate samples. **C**, ELISA measurement of secreted IL-6 in cell culture media 3 hours after 50 ng/mL TNF- α in E-PZ and E-CA cells pretreated for 14 hours with vehicle (light columns) or 50 nmol/L 1,25D (dark columns).

tissues has not been fully characterized but seems to be transcriptional rather than posttranscriptional (34).

Although proinflammatory factors are overexpressed in PCa, it is unclear whether increased levels of these factors are required for development of the cancer originally or are a consequence of the cancer. On one hand, inflammation may trigger the initial expression of these factors in normal prostate tissue and when PCa arises, the PCa cells maintain these features for a survival advantage. On the other hand, because there is significant inflammatory infiltrate in PCa lesions, the possibility of the inflammatory genes becoming expressed later in PCa development cannot be excluded. If the former situation occurs, then our results suggest that the ability of 1,25D to suppress the synthesis of IL-6, and perhaps other inflammatory factors, may be a key component in blocking carcinogenic events associated with inflammation.

Another important finding from our study was that 1,25D up-regulated MKP5 in primary cultures derived from normal prostatic

epithelium or primary adenocarcinomas of the prostate and in SV40 Tag-immortalized prostatic epithelial pRNS-1-1 cells, but not in the prostatic stromal cells or in PCa cell lines. pRNS-1-1 cells are not sensitive to growth inhibition by 1,25D yet retain functional VDR (1). Stromal cells (F-PZ) derived from normal prostatic tissue and PCa cell lines did not induce MKP5 when treated with 1,25D although these cells express VDR and are growth-inhibited by 1,25D (1). Furthermore, the squamous cell carcinoma cell lines A431 and SCC-25 displayed attenuated MKP5 up-regulation following 1,25D treatment compared with normal keratinocytes although they too retain VDR and growth inhibition by 1,25D (35, 36). We observed up-regulation of MKP5 by 1,25D in the matched pairs of E-PZ and E-CA cells from individual patients. These E-CA cells were derived from localized PCa whereas PC-3, DU 145, and LNCaP were all derived from PCa metastases. These data suggest that localized PCa may still be responsive to the anti-inflammatory properties of vitamin D. Together these observations show that (a) induction of MKP5 by

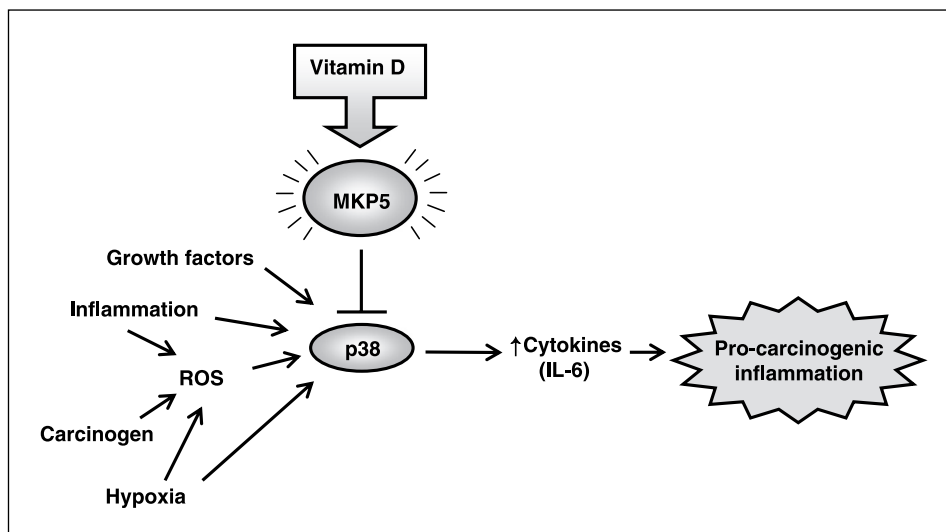


Figure 7. Proposed mechanism for anti-inflammatory activity and PCA prevention by vitamin D.

1,25D is specific to normal and localized malignant prostatic epithelial cells and does not occur in normal prostatic stromal cells; (b) induction of MKP5 is independent of growth inhibition by 1,25D; and (c) lack of 1,25D-induced MKP5 in PCa cell lines is not a result of immortalization per se because immortalized pRNS-1-1 cells up-regulate MKP5 in response to 1,25D.

The quantitative RT-PCR data show that the basal levels of MKP5 are lower in the PCa cell lines compared with normal prostatic epithelial cells. Because the established metastasis-derived PCa cell lines have low levels of MKP5 and are unable to induce MKP5 in response to 1,25D, it is tempting to speculate that loss of MKP5 may occur during PCa progression as the result of selective pressure to eliminate tumor suppressor activity of MKP5 and/or 1,25D. A number of MKP family members have been suggested to be tumor suppressors. In PCa MKP1 has been shown to be down-regulated (37). Candidate MKP tumor suppressors in other malignancies include MKP7, which is frequently deleted in lymphoblastic leukemia (38), MKP3, hypermethylated or deleted in pancreatic cancer (39, 40), and MKP2, which is deleted in breast carcinoma (41).

The link between inhibition of p38 by 1,25D via MKP5 and PCa prevention becomes more apparent when the many different ways the p38 pathway may become activated are considered. In addition to inflammatory cytokines, osmotic stress, UV irradiation (which we used in these studies), reactive oxygen species and hypoxia also activate p38 (42). Reactive oxygen species can amplify p38 activation because they are generated during hypoxia and as a by-product of inflammation (refs. 6, 8; Fig. 7). Hypoxia has been implicated in PCa metastasis and progression to androgen independence (6).

In addition to a potential role in PCa prevention, p38 inhibition by 1,25D via MKP5 may be farther reaching and mitigate activities of vitamin D in other tissues. Recent cDNA microarray analyses have shown MKP5 up-regulation by vitamin D in skin (43), colon (44), and ovarian cells (45). Furthermore, the overall immunomodulatory activity of vitamin D on the VDR-expressing cells of the innate and adaptive immune system (46) is highly similar to the

immunomodulatory role of MKP5 that was shown by Zhang et al. (47) using MKP5 knockout mice. The mechanism by which vitamin D reduced IL-6 mRNA stability, through MKP5-mediated p38 inactivation, may also be responsible for down-regulation of other mRNAs. Activation of the p38 pathway causes a robust and rapid increase in inflammatory response proteins by mRNA stabilization and increased translation through AU-rich elements in the 3' untranslated region (UTR; ref. 48). Posttranscriptional regulation of inflammatory genes is the basis for the anti-inflammatory activity of p38 inhibitors (48). Decreased mRNA stabilization by vitamin D has been shown to mediate down-regulation of granulocyte macrophage colony-stimulating factor (49) and this mechanism may decrease the stability of other AU-rich 3'-UTR-containing proinflammatory mRNAs by vitamin D.

It is becoming apparent that inflammation, both chronic and acute, contributes to PCa development. The epidemiologic evidence combined with the molecular pathogenesis of PCa supports this hypothesis (7). If inflammation is a significant risk factor for PCa, then PCa prevention will best be achieved with agents, such as vitamin D, which inhibit inflammation and/or decrease the cellular stress response that accompanies inflammation. Our study shows that MKP5 is a mediator of anti-inflammatory effects of 1,25D and suggests that vitamin D may play a significant role in PCa prevention by facilitating p38 inhibition and reduced IL-6 production in prostatic epithelial cells.

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α -Methylacyl-CoA Racemase: A New Molecular Marker for Prostate Cancer¹

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Abstract

Identification of genes that are dysregulated in association with prostate carcinogenesis can provide disease markers and clues relevant to disease etiology. Of particular interest as candidate markers of disease are those genes that are frequently overexpressed. In this study, we describe a gene, α -methylacyl-CoA racemase (AMACR), whose expression is consistently up-regulated in prostate cancer. Analysis of mRNA levels of AMACR revealed an average up-regulation of ~9 fold in clinical prostate cancer specimens compared with normal. Western blot and immunohistochemical analysis confirms the up-regulation at the protein level and localizes the enzyme predominantly to the peroxisomal compartment of prostate cancer cells. A detailed immunohistochemical analysis of samples from 168 primary prostate cancer cases using both standard slides and tissue microarrays demonstrates that both prostate carcinomas and the presumed precursor lesion (high-grade prostatic intraepithelial neoplasia) consistently scored significantly higher than matched normal prostate epithelium; 88% of the carcinomas had a staining score higher than the highest score observed for any sample of normal prostate epithelium. Both untreated metastases ($n = 32$ patients) and hormone refractory prostate cancers ($n = 14$ patients) were generally strongly positive for AMACR. To extend the utility of this marker for prostate cancer diagnosis, we combined staining for cytoplasmic AMACR with staining for the nuclear protein, p63, a basal cell marker in the prostate that is absent in prostate cancer. In a simple assay that can be useful for the diagnosis of prostate cancer on both biopsy and surgical specimens, combined staining for p63 and AMACR resulted in a staining pattern that greatly facilitated the identification of malignant prostate cells. The enzyme encoded by the AMACR gene plays a critical role in peroxisomal β oxidation of branched chain fatty acid molecules. These observations could have important epidemiological and preventive implications for prostate cancer, as the main sources of branched chain fatty acids are dairy products and beef, the consumption of which has been associated with an increased risk for prostate cancer in multiple studies. On the basis of its consistency and magnitude of cancer cell-specific expression, we propose AMACR as an important new marker of prostate cancer and that its use in combination with p63 staining will form the basis for an improved staining method for the identification of prostate carcinomas. Furthermore, the absence of AMACR staining in the vast majority of normal tissues coupled with its enzymatic activity makes AMACR the ideal candidate for development of molecular probes for the noninvasive identification of prostate cancer by imaging modalities.

Introduction

Prostate cancer initiation and progression are processes involving multiple molecular alterations (1). Genomic alterations, combined

with changes in the tissue microenvironment, lead inevitably to altered levels of expression of many individual genes in tumor cells. Identification of these genes represents a critical step toward a thorough understanding of prostate carcinogenesis and an improved management of prostate cancer patients. Of particular biological and clinical interest are those genes that are consistently overexpressed in the vast majority of prostate cancers. Such genes and their products, besides providing possibly valuable insight into the etiology of prostate cancer, may have important utility as diagnostic markers in this disease. However, few genes of this nature have been reported to date.

High-throughput gene expression profiling using cDNA microarray allows for systematic interrogation of transcriptionally altered genes. By comparing the mRNA expression profile of cancerous lesions with noncancerous lesions, multiple candidates of molecular markers for prostate cancer have emerged (2–6). One such candidate, the gene for AMACR,³ was identified as being overexpressed in prostate carcinoma cells when compared with benign or normal prostate epithelial cells (2, 3). AMACR is a well-characterized enzyme (7) that plays a key role in peroxisomal β -oxidation of dietary branched-chain fatty acids and C27-bile acid intermediates. It catalyzes the conversion of (R)- α -methyl-branched-chain fatty acyl-CoA esters to their (S)-stereoisomers. Only the (S)-stereoisomers can serve as substrates for branched-chain acyl-CoA oxidase during their subsequent peroxisomal β -oxidation. Two aspects of this pathway may have particular relevance for prostate carcinogenesis: (a) the main sources of branched chain fatty acids in humans (milk, beef, and dairy products; Ref. 8) have been implicated as dietary risk factors for prostate cancer (9); and (b) peroxisomal β -oxidation generates hydrogen peroxide (10), a potential source of procarcinogenic oxidative damage (11, 12).

An initial report by Xu *et al.* (2), using a limited number of samples, indicated that AMACR was overexpressed potentially in a subset of prostate cancers at both the mRNA and protein level. Our previous study compared gene expression profiles of 16 prostate cancer and 9 samples of BPH using cDNA microarrays containing 6500 human genes (3). AMACR was expressed highly in the majority of prostate cancer samples, averaging ~6-fold higher levels than the BPH samples. In this study, we expanded these previous studies by including cDNA microarray data from an additional 35 prostate tissue samples, comprising matched normal tumor pairs, and by performing an extensive IHC analysis of both primary and metastatic prostate cancer specimens, including normal and cancerous prostate tissue from 159 patients analyzed on prostate TMAs. Furthermore, we examined the diagnostic utility of combining staining for AMACR with staining for p63, a prostate basal cell marker that is absent in the vast majority of prostate cancers (13, 14). The consistent and extensive up-regulation

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³The abbreviations used are: AMACR, α -methylacyl-CoA racemase; IHC, immunohistochemical; KRT8, keratin 8; PIN, prostatic intraepithelial neoplasia; TMA, tissue microarray; BPH, benign prostatic hyperplasia; TBP, TATA-binding protein; GSTP1, glutathione S-transferase π ; HGPIN, high-grade prostatic intraepithelial neoplasia.

of AMACR that we observe at both the mRNA and protein level strongly suggests that AMACR will be an important new marker for prostate cancer.

Materials and Methods

Prostate Tissue Procurement for cDNA Microarray Analysis. Prostate cancer tissue specimens for cDNA microarray analysis were obtained from 23 patients undergoing radical prostatectomy for clinically localized prostate carcinoma at Johns Hopkins Hospital from 1993 to 2000. Specimens were obtained from the operating room immediately after resection. The seminal vesicles were truncated. If palpable tumor was identified, the specimen was inked and harvested as described previously (15). This results in the banking of the largest palpable tumor, as well as areas of apparent normal and BPH when available. The areas containing tumor that were adjacent to the harvested tumor blocks were submitted for formalin fixation and routine processing. Harvested tissues were flash frozen and stored in -80°C . Paired normal cancer samples were prepared as described previously (3) from 12 of the 23 specimens, whereas only cancer samples were obtained from the other 11 specimens, giving 35 samples total for analysis. Cancer samples were microscopically estimated to contain $\geq 60\%$ (range from 60 to 90%) adenocarcinoma cells in cellular composition, and the normal samples were estimated to contain $\geq 50\%$ (range from 50 to 75%) epithelial cells. Institutional Review Board-approved informed consent was obtained from all patients in this study.

cDNA Microarray Analysis. RNA extraction, labeling, and hybridization were carried out as described previously (3). A single reference sample composed of a pool of RNA from two BPH specimens was used throughout all hybridizations. Measurement values were extracted for normalized ratios of signal intensities of sample *versus* reference, which represent the relative mRNA abundance for each gene in each sample when compared with the common reference (3).

Real-time Reverse Transcription-PCR. Quantitative PCR was performed on iCycler (Bio-Rad, Richmond, CA) with gene-specific primers (AMACR: 5'-GAATCCGTATGCCCGCTGAATCT-3' and 5'-ACCCTTGCCAGTGCCTGTGC-3'; TBP: 5'-CACGAACACGGCACTGATT-3' and 5'-TTTTCTTGCTGCCAGTCTGGAC-3'), as described previously (16). A standard curve was generated by serial dilution of plasmids containing the specific amplicons assayed. AMACR mRNA copy number was normalized to TBP.

Western Blot Analysis. Protein (25 μg) was subjected to SDS-polyacrylamide (10%) gel electrophoresis, transferred to nitrocellulose (Amersham Pharmacia Biotech, Piscataway, NJ), probed with AMACR antiserum (7) at a 1:2000 dilution, and detected by enhanced chemiluminescence (Amersham Pharmacia Biotech) as described previously (16).

TMA: Construction and Analysis. A total of 159 radical prostatectomy specimens were selected randomly out of a total of >400 cases performed between 1/1/2000 and 8/1/2001 at Johns Hopkins Hospital and used to construct TMAs as described previously (16). Areas representing the largest carcinoma present, as well as areas of normal appearing prostate epithelium, were circled on the glass slides. For each sample of tumor and normal, four tissue cores were taken for TMA construction. Although there is no universal method of sampling prostate cancer tissue for IHC studies, using either standard slides or TMAs, the histological features of these areas that we sampled generally reflect the final Gleason score for the case. Stained TMA slides were scanned using the BLISS imaging system as described by Manley *et al.* (17). Each array spot was then formed into a composite image and viewed and scored on a personal computer monitor as described (16). Data were then further summarized, and statistical analysis was performed using Stata 6.0 and SAS for Microsoft Windows.

Prostate Adenocarcinoma Tissue from Standard Slides. For a number of the cases, standard slides were used to assess overall percentage of positive cells in the tumors and normal tissues and also to further evaluate expression in HGPIN and BPH.

Metastatic Prostate Cancers. For metastatic carcinoma, standard slides from specimens (pelvic lymph node, soft tissue, and bone metastases) from patients with nonhormone refractory tumors were obtained from the archives of the Department of Pathology at The Johns Hopkins University. For hormone refractory cancer specimens, tissues were obtained as a single TMA from the University of Michigan, Specialized Programs of Research Excellence core tissue facility.

IHC Staining. Staining for AMACR was carried out using the Envision+ kit (DAKO Corp., Carpinteria, CA). Briefly deparaffinized slides were hydrated and then placed in citrate buffer (pH 6.0) and steamed for 14 min. Endogenous peroxidase activity was quenched by incubation with DAKO peroxidase block for 5 min at room temperature. Slides were then washed and incubated with primary antibody (1:16,000 dilution of antiserum) overnight at 4°C . Secondary anti-rabbit antibody-coated polymer peroxidase complex was applied for 30 min at room temperature. Substrate/chromogen was applied and incubated for 5–10 min at room temperature. Slides were counterstained with hematoxylin. For double labeling of AMACR and p63, the anti-p63 mouse monoclonal antibody cocktail (1:100 dilution; Lab Vision Corp., Fremont, CA) was added after the anti-racemese antibody incubation and incubated for 45 min at room temperature. The secondary anti-rabbit and antimouse HRP conjugates were sequentially added, and the reaction was developed as above.

Scoring of IHC Staining. A scoring method was based on the fact that the specimens clearly showed a varying degree of staining intensity and percentage of cells staining. Therefore, a combined intensity and percentage positive scoring method was used (18). Strong intensity staining was scored as 3, moderate as 2, weak as 1, and negative as 0. For each intensity score, the percentage of cells with that score was estimated visually. A combined weighted score consisting of the sum of the percentage of cells staining at each intensity level was calculated for each sample, *e.g.*, a case with 70% strong staining, 10% moderate staining, and 20% weak staining would receive a score as follows: $(70 \times 3 + 10 \times 2 + 20 \times 1) = 250$. The maximum score is 300.

Results

Analysis of Paired Samples of Normal and Cancerous Prostate

Tissue mRNA. In the previous study, we used weighted gene and random permutation analysis to identify 210 genes with statistically different levels of mRNA expression between prostate cancer and BPH (3). Among these genes, AMACR maintained consistently low levels of expression in 9 of 9 BPH samples (signal intensities in the lowest quartile of all genes analyzed) but was overexpressed by an average of 5.7-fold in 13 of 16 cancer samples. We have since generated mRNA profiles of an additional 35 prostate samples, including 12 matched normal cancer pairs and 11 nonpaired cancer samples (data set in preparation for publication) by comparing each sample to a common reference (from BPH). To illustrate the expression pattern of AMACR in these samples in relation to other genes whose expression in prostate tissues has been well documented previously, we extracted expression ratios for AMACR (IMAGE clone ID: 133130), along with those for GSTP1 (IMAGE clone ID: 136235) and KRT8 (IMAGE clone ID: 897781). Reduced GSTP1 expression because of "CpG island" hypermethylation is found in $>90\%$ of prostate cancers (19), and KRT8 mRNA is expressed constitutively in the epithelial cells of normal and cancerous prostate tissues (20). As shown in Fig. 1, the majority (20 of 23) of the cancer samples demonstrated overexpression of AMACR mRNA compared with the BPH reference. When the cancer samples were compared with their matching normal samples, AMACR was overexpressed in the cancer samples in 9 of 12 pairs. Moderate overexpression compared with the reference (an average of 3-fold) was also observed in 3 of the 12 normal samples. Consistent with previous reports, GSTP1 expression was down-regulated in the majority of cancer samples compared with BPH reference or their matching normal samples. Expression of KRT8, an epithelial marker, showed little variation among all of the samples, indicating that the sample preparation was effective to enrich and balance the epithelial content in the samples analyzed.

A quantitative reverse transcription-PCR assay was used to estimate the relative difference in AMACR mRNA abundance in samples of normal and cancerous prostate tissue. Although extensive variability was observed, the copy number of AMACR mRNA in prostate cancer specimens was on average 8.8-fold higher than the value for normal prostate samples (average = 60.9, SD = 84.3, range 0.6–260.4, $n = 8$, for cancer samples compared with an average of 6.9,

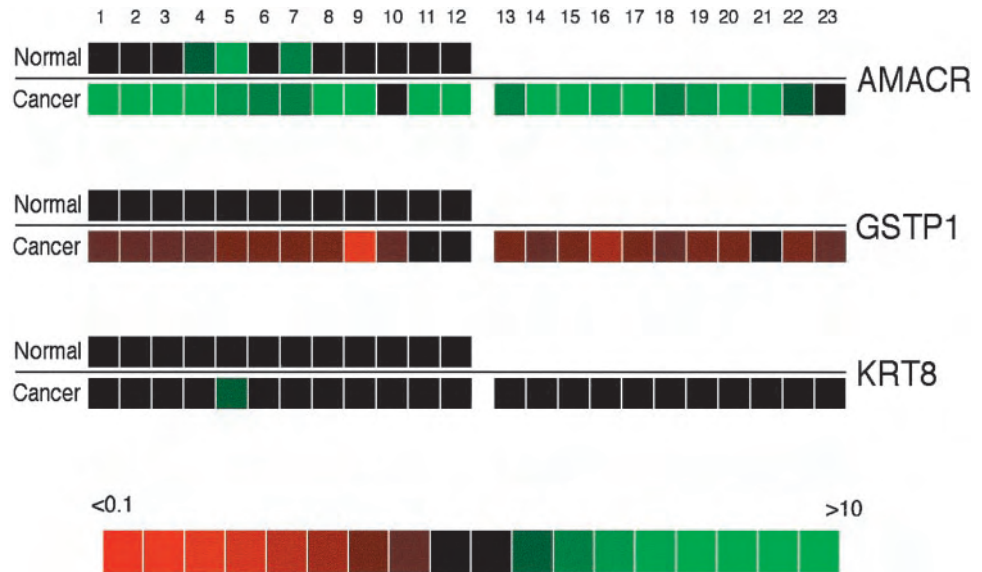


Fig. 1 Gene expression ratios for AMACR, GSTP1, and KRT8. Each colored square represents the relative mRNA abundance (ratio of sample:reference) in each sample compared with the common BPH reference. Each of the 12 normal samples (1–12) was paired with its matching cancer sample below the black line and the other 11 nonpaired cancer samples (13–23) positioned at the right side below the line. The measured expression ratios for each gene were presented graphically as colored squares, with the green squares representing higher expression in sample compared with the reference (BPH), the red squares meaning lower expression in sample than reference (BPH), and black squares indicating a ratio of ~ 1 . Color intensities are scaled according to the ratio (sample:reference) as shown at the bottom, with the brightest color having a ratio of >10 (green) or <0.1 (red).

SD = 9.9, range 0.51–32.9, $n = 8$, for normal) when normalized against copies of TBP. Similarly, the median value for the cancer samples was 7.8-fold higher than for the normal samples.

Western Blot Analysis of AMACR Protein. Expression of AMACR protein was examined using an antiserum demonstrated previously to be specific for this antigen (7). Western blot detection of AMACR in liver, as a positive control (7), and a series of prostate tissue samples is shown in Fig. 2. Although a M_r 47,000 band corresponding to AMACR protein was readily detected in liver and each of the prostate cancer specimens, little or no reactivity was observed in the corresponding normal specimens or any of the BPH samples assayed.

IHC Analysis of Radical Prostatectomy Specimens Using Standard Slides. To obtain the pattern of staining of AMACR in prostate tissues, we examined clinically localized prostate adenocarcinoma specimens using representative standard slides containing normal epithelium, carcinoma, and HGPIN. We used a scoring method that accounts for both the intensity of staining and the percentage of cells staining. In general, normal prostate epithelium was either negative or weakly positive ($n = 14$ areas from 12 patients, median score = 15, mean score = 19, SD = 22; Fig. 3). Prostate stroma, inflammatory cells, endothelial cells, and nerves were uniformly negative (Fig. 3). Strikingly, adenocarcinomas showed highly intense staining in the majority of tumor cells in most cases ($n = 19$ carcinoma lesions from 14 patients, median = 290, mean = 277, SD = 30; Fig. 3). The staining was uniformly cytoplasmic and was typically found in small punctate, microbody structures, consistent with the previously reported localization of AMACR predominantly to peroxisomes and mitochondria (7). Staining in HGPIN was also generally positive, although the staining was more variable and often less intense than adjacent carcinoma (Fig. 3, C and D; $n = 10$ areas from 6 patients, median 170, mean 179, SD = 63). Staining in atrophic areas was generally negative or positive in a small percentage of cells ($n = 5$ areas from 3 patients, median = 30, mean = 30, SD = 22). Staining in BPH was generally negative or focally, weakly positive ($n = 6$ areas from 4 patients, median = 20, mean = 20, SD = 8.9).

IHC Analysis of Radical Prostatectomy Specimens Using TMAs. To survey many tumor and normal specimens, four high-density TMAs, designed to contain samples of clinically localized prostate cancer and matched normal appearing epithelium from 159

patients, were stained. The median age of patients in these TMAs was 58 (range 40–73), and the median prostate-specific antigen was 6.4 (mean 7.5, SD 4.6, range 1.2–38). Array spots (1578) were imaged. The majority of array spots (79%) contained tissue that was readily readable. Of the usable array spot images, 209 were control normal (nonprostatic) tissues. Of the array spots scored for AMACR staining, 417 spots contained adenocarcinoma (334 Gleason pattern 3, 62 Gleason pattern 4, 15 Gleason pattern 5, 4 Gleason pattern 2, 1 ductal adenocarcinoma, 1 pseudo-hyperplastic carcinoma) from 142 patients, 442 spots contained normal prostate epithelium from 144 patients of the patients, and 27 spots contained HGPIN from 23 patients. Other spots consisted of prostate stroma only, atrophy, or were difficult to interpret.

For normal prostate and adenocarcinoma, between 2.5 and 3 TMA spots (duplicate spots) were scored from each patient. For statistical analyses, the mean of the individual spot scores were computed so that for each tissue type from each patient, there was a single IHC score for comparison. Using these mean scores, the AMACR IHC scores for both carcinoma and HGPIN were highly statistically significantly different from normal (Fig. 4, carcinoma versus normal, $P < 0.0001$;

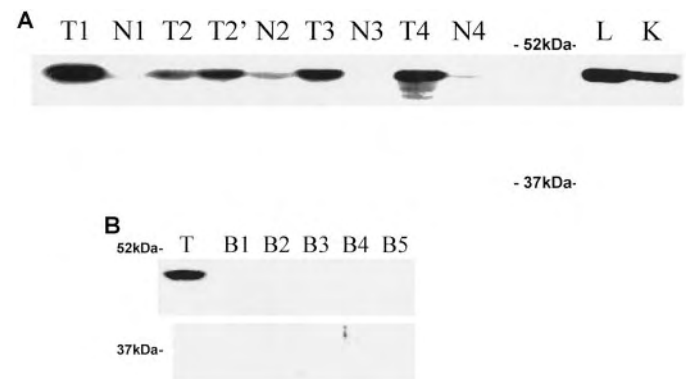


Fig. 2. Western blot analysis of AMACR protein. Total tissue protein (25 μ g) was analyzed using anti-AMACR antiserum. In A, pairs of tumor and corresponding normal tissue from 4 patients are designated by T1, T2, T3, T4, and N1, N2, N3, N4, respectively. For the second patient, there were two apparently independent tumors sampled (T2 and T2'). L, liver and K, kidney. In B, five different samples of BPH tissue (B1–B5) were analyzed together with a single sample of prostate cancer (T). The position of pre-stained molecular weight markers (ovalbumin at M_r 52,000 and carbonic anhydrase at M_r 37,000) is marked.

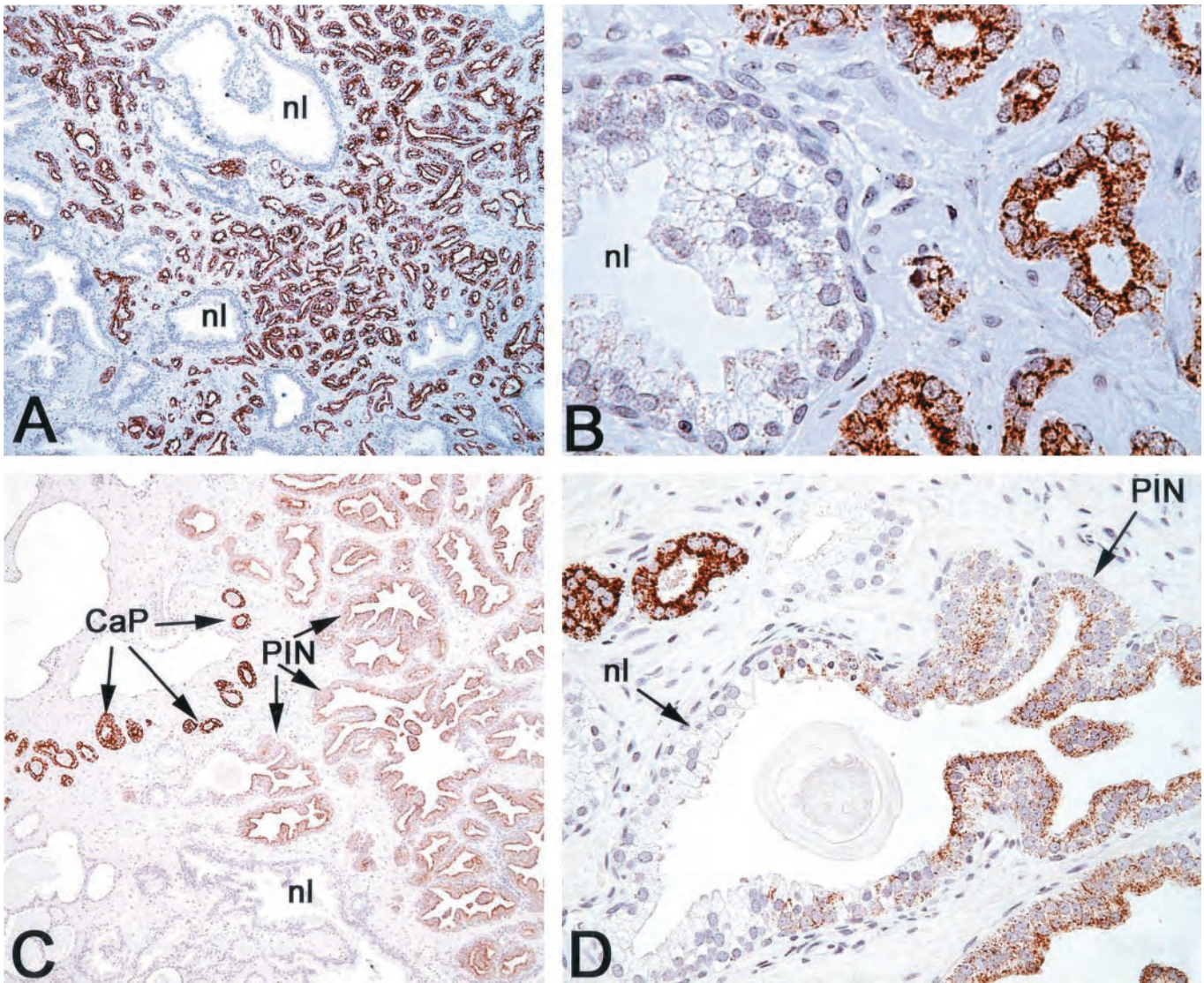


Fig. 3. IHC localization of AMACR in prostate tissue using standard slides. *A*, low-power image of Gleason pattern 3 carcinoma infiltrating between benign normal appearing glands (*nl*) showing homogeneous strong staining ($\times 40$). *B*, higher power view of representative region from *A* showing punctate cytoplasmic staining ($\times 400$). *C*, another case showing high-intensity staining in carcinoma (*CaP*), intermediate intensity staining in HGPIN (*PIN*), and no staining in normal (*nl*; $\times 100$). *D*, higher power view of *C* showing strong staining in carcinoma glands (*top left*) and staining in acinus in that is involved partially with HGPIN with staining only in atypical HGPIN cells (*PIN*). Note negative staining in the normal appearing acinus just to the *right* of the carcinoma ($\times 200$).

HGPIN versus normal, $P < 0.001$, Wilcoxon's rank-sum test). The score for HGPIN was significantly less than the score for carcinoma ($P = 0.0002$, Wilcoxon's rank-sum test). If a cutoff of ≥ 100 is used for positive staining, then 95.6% of carcinomas were positive, whereas 3.5% (5 of 144) of normal epithelium was positive. Using a score of ≥ 150 for strong positive staining, then 88% of the carcinomas would be considered strong, versus none of the normal epithelium. The carcinomas (52%) had a median score of 300 (the maximum).

The distribution of AMACR mean IHC scores for carcinoma (mean for all of the spots for each patient) stratified by Gleason score and pathological stage is shown in Table 1. There was no relation between AMACR IHC score and Gleason grade, pathological stage, patient age, or preoperative serum prostate-specific antigen (Kruskal-Wallis, all $P_s > 0.05$). As expected, Gleason score at radical prostatectomy was associated strongly with higher stage disease (Spearman's rank correlation coefficient = 0.42, $n = 142$, $P < 0.0001$; Table 1).

IHC Analysis of Prostate Cancer Metastases. Staining in metastatic prostate cancers from nonhormone refractory disease ($n = 32$

sites from 32 patients: 8 bone, 21 pelvic lymph node, 2 soft tissue, and 1 lung) showed staining in the majority of cases (data not shown). The median score in nontreated metastatic cases was 240 (mean 204, SD 97). By the criteria stated above for positivity, 81% (26 of 32) were positive, and 62.5% were strongly positive (20 of 32). In hormone refractory metastatic prostate ($n = 25$ sites from 14 patients), the median score was 215 (mean = 206, SD = 84). Thus, 93% (13 of 14) of hormone refractory metastatic cancers were positive, and 71.4% were strongly positive.

AMACR Protein Expression in Other Normal Tissues. To examine the overall tissue distribution of AMACR protein expression, staining was performed using a TMA containing a wide variety of human tissues. Staining was strongly positive in virtually all hepatocytes, proximal kidney tubules, and glomerular epithelial cells of the kidney (data not shown). Moderate staining was found in the acinar cells and some ductal cells of major salivary glands. Weak staining was found in distal tubules and collecting ducts of the kidney. Other tissues showed weak and heterogeneous expression, including the following: (a) neurons in the central nervous system; (b) absorptive

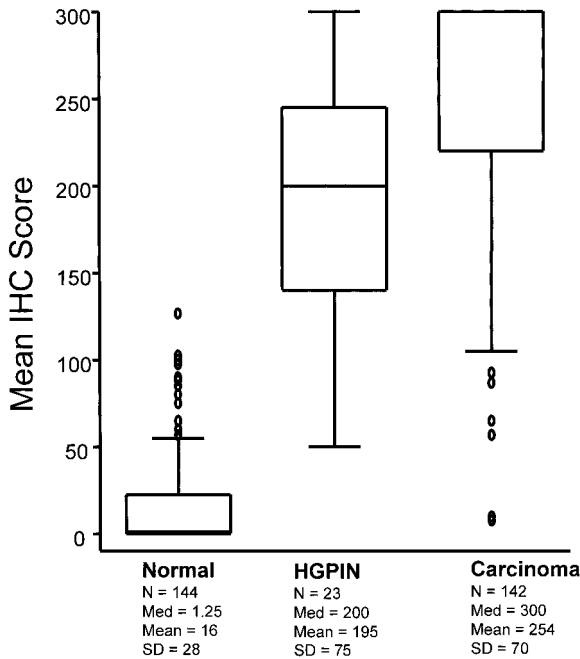


Fig. 4. Relative expression of AMACR by IHC score in normal, HGPIN, and carcinoma by scoring of TMA spots. Box shows 25th-75th percentiles, as well as median (center line). Whiskers show 5th and 95th percentiles, and ovals represent outliers.

and paneth cells of the small bowel; (c) absorptive cells of the large bowel; and (d) Sertoli cells of the testis. Staining was not detectable in the urinary bladder, ovary, endometrium, fallopian tube, uterine cervix, breast, lung, skin, tonsil, lymph nodes, thymus, spleen, laryngeal epithelium, minor salivary glands, pancreas, gall bladder, thyroid, stomach, esophagus, skeletal muscle, or smooth muscle.

Combination of AMACR Staining with p63 Facilitates Detection of Prostate Cancer Cells. The intense staining in tumors with weak staining in normal suggested that AMACR IHC staining might be useful as an adjunct to the diagnosis of prostate cancer on needle biopsy or other clinical specimens. To be useful as a potential diagnostic marker for prostate cancer, carcinoma lesions need to be separated reliably from lesions of HGPIN and other potential mimickers of prostate cancer, such as adenosis and atrophy, as well as from normal prostate tissue. On small needle biopsy samples, this distinction can sometimes be problematic (21). One very useful tool has been IHC staining for basal cell-specific cytokeratins, typically using the 34BE12 monoclonal antibody (22). Because basal cells, which are absent in the vast majority of prostatic adenocarcinomas, are present in normal glands, benign mimickers, such as atrophy and adenosis, and in HGPIN, staining for basal cell cytokeratins is often used in prostate cancer needle biopsies (22). More recently, the p63 protein has been found to be localized to the nuclei of basal cells in prostate epithelium with a basal cell-specific staining pattern nearly identical to 34BE12 (13, 14). Because the staining for p63 is strictly nuclear and is negative in the vast majority of carcinomas, and the staining for AMCAR is cytoplasmic and only strong in carcinoma or HGPIN, we combined the staining for these two markers as a cocktail. There was strong staining of the nuclei of basal cells in benign glands, whereas carcinoma showed no nuclear staining but strong cytoplasmic staining, with no decrease as compared with AMCAR staining alone ($n = 20$, Fig. 5, A and B). HGPIN showed variable punctate, cytoplasmic AMCAR staining, but strong and homogeneous nuclear staining in basal cells, thus allowing one to reliably distinguish HGPIN from carcinoma (Fig. 5, C and D). At times, HGPIN appeared to contain buds of epithelium, pinching off into the underlying stroma

(23). An example of this phenomenon is shown in Fig. 5D (arrow), where a single acinus is projecting from an acinus containing HGPIN. The projecting acinus shows very sparse p63 basal cell staining, consistent with early invasion. The surrounding carcinoma cells show complete loss of p63 staining, yet they contain AMACR cytoplasmic staining.

Discussion

In this study, we demonstrate that AMACR is overexpressed in the majority of prostate cancers and cancer cells within these tumors. Using many cases with diverse pathologic characteristics, we find that overexpression at the protein level is very tightly linked to prostate cancer and occurs in virtually all grades and stages and in both hormone refractory and untreated cases. Over 95% of prostate cancers analyzed stained positively for AMACR, whereas <4% of histologically normal prostate epithelium was positive. Using a more stringent scoring scheme, these values are 88 and 0% for cancers and normal cells that are positive, respectively. Because there appears to be such a tight link between overexpression and the histological prostate cancer phenotype, these finding have implications for the pathogenesis, diagnosis, imaging, and treatment of prostate cancer.

In terms of early diagnosis on prostate needle biopsy, whereas basal cell-specific keratin is a useful aid for diagnosis, this marker is lost in prostate cancer. Because there can be artifactual loss of IHC staining, at times, this staining is uninformative and/or misleading. To date, few, if any, validated markers of prostate cancer have been identified that are overexpressed consistently as detected by IHC staining such that they might be of diagnostic use in a large percentage of cases. We now show that AMACR may provide the first example of such a marker. Because AMACR staining can occur intensely in HGPIN, we combined staining using AMACR with staining for p63. Because these markers, when present, are invariably cytoplasmic and nuclear, respectively, there is no need for the use of two color staining. p63 staining has been shown to be comparable with the basal cell-specific keratin 34βE12 monoclonal antibody but has the advantage in this case of a more clearly discernible nuclear location (13, 14). Thus, AMACR is a new positive stain that complements the traditional negative stain to enhance prostate cancer diagnosis. To determine the usefulness of AMACR in diagnostic pathology practice, we have begun to use clinical needle biopsies in prospective studies comparing AMACR, AMACR/p63, and basal cell-specific cytokeratins. Additionally, this marker combination could be of use for nonpathologist researchers studying prostate cancer specimens to enhance diagnostic certainty.

The enzyme encoded by this gene plays a critical role in the metabolism of fatty acid molecules, specifically by peroxisomal β

Table 1 AMACR IHC score from TMA analysis for 142 patients stratified by Gleason grade and pathological stage at radical prostatectomy

Grade		Stage			
		T2	T3A	T3B	N1
5-6	n	65	12	2	0
	Median	300	268	258	Na ^a
	Mean	255	218	258	Na
	SD	68	100	60	Na
7	n	24	14	5	1
	Median	293	300	243	300
	Mean	238	263	254	300
	SD	83	60	43	0
8-9	n	5	10	3	1
	Median	300	300	283	300
	Mean	297	274	273	300
	SD	8	58	34	0

^a Na, not applicable.

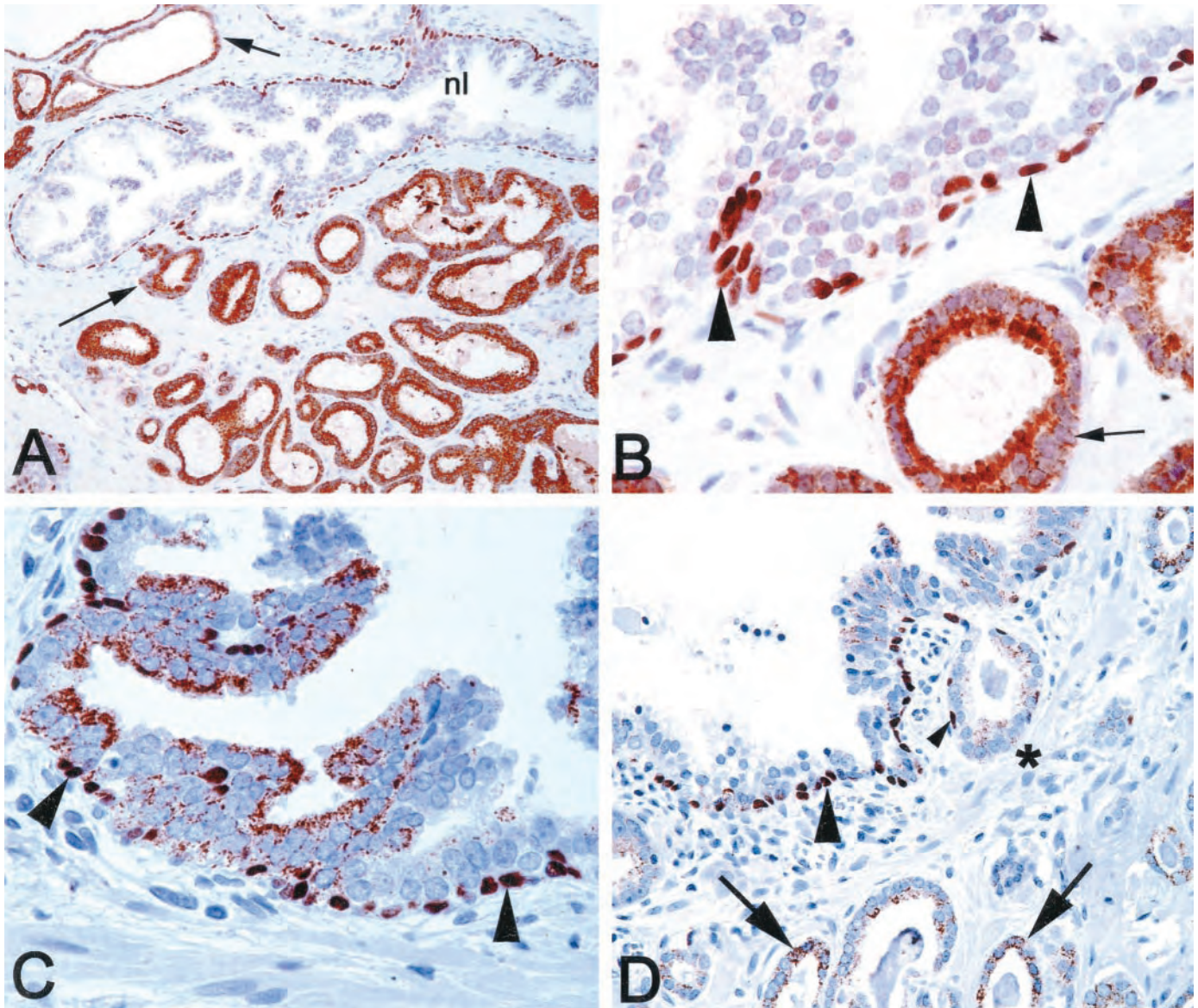


Fig. 5. Simultaneous single color localization of p63 and AMACR. Tissues were stained with a cocktail containing anti-p63 (nuclear) and anti-AMACR (punctate cytoplasmic) antibodies, and staining was localized simultaneously. In A, nuclear basal cell staining (p63) is apparent in normal appearing acinus. Arrows, infiltrating carcinoma cells ($\times 100$). B, higher power view of A. Arrowheads, nuclear basal cells staining (p63); arrow, carcinoma ($\times 400$). C, HGPIN showing moderate to weak punctate cytoplasmic AMACR staining and strong positive staining p63 staining of basal cells ($\times 400$). D, HGPIN (top gland) with weak cytoplasmic AMACR staining and nuclear basal cells staining (p63). Note small acinus apparently budding off (*) of HGPIN gland showing very sparse basal cell nuclear staining (arrowhead). Below, there is moderate to weak intensity cytoplasmic staining in infiltrating carcinoma cells that lack p63 nuclear staining.

oxidation (10). Branched chain fatty acids, which originate almost entirely from the diet, contain methyl groups in the R position, whereas the enzymes of the β oxidation pathway can only transform substrates having the S configuration (10). The enzyme AMACR catalyzes this interconversion. One implication of the up-regulation of AMACR is that prostate cancer cells may have a consistently greater capacity to metabolize dietary branched chain fatty acids than would their normal counterparts. Although the contribution of this up-regulation to prostate carcinogenesis, if any, is unclear at present, two interesting aspects of this pathway may be relevant: (a) the first step of the pathway in β oxidation of branched chain fatty acids is an oxidation step catalyzed by acyl-CoA oxidases, with the products being oxidized substrate and hydrogen peroxide (10). Experimental overexpression of acyl-CoA oxidase can transform cells (12), and the increase in oxidative stress because of the production of hydrogen peroxide by this pathway has been proposed to play a role in the

transformation process (11). Indeed, the potent carcinogenic activity of peroxisome proliferators in animal models is thought to be mediated, at least in part, by up-regulation of the peroxide-producing enzymes of the peroxisome (24); and (b) the primary branched chain fatty acid whose metabolism is critically dependent on the action of AMACR is phytanic acid, derived from phytol, a breakdown product of chlorophyll in ruminants. This fatty acid is found primarily in cow's milk, and dairy products derived there from, as well as beef but not meat from chickens or some fish (25). An interesting question is whether the increased risk for prostate cancer conferred by consumption of dairy products and/or red meat (9) is related to the up-regulation of this enzyme and its associated pathway in the early stages of prostate carcinogenesis, e.g., in PIN.

Molecular imaging promises the ability to identify individual cells or groups of cells expressing specific proteins or enzymatic activity in real time in living patients (see Louie *et al.*; Ref. 26) The ability to

image AMACR protein or enzymatic activity would likely provide significant value in localization of primary prostate cancer within the prostate. A first application of this would be to help direct the location of needle biopsy sites in the prostate and possibly to assess the extent of cancer within the prostate. In addition, the ability to image AMACR systemically would provide value for detection of metastatic prostate cancer in organs other than the liver and kidney.

The prostate glands of U.S. men are biopsied >1 million times a year, leading to a positive diagnoses of ~180,000 new prostate cancer cases annually. Estimates of equivocal or ambiguous biopsy evaluations that are suspicious for cancer range from 0.3 to 24% (21), resulting in tens of thousands of repeat biopsies. Clearly, markers, which can assist in the accurate evaluation of prostate needle biopsies, are needed urgently. Because of its consistency and robustness, AMACR appears to fit the criteria for such a marker and as such may become routinely used in the pathological diagnosis of prostate cancer. In addition, the biological function of this marker provides exciting new information regarding the etiology of prostate cancer and provides a novel target for prevention and therapeutics. Whether this marker is pathogenic, a potential drug, or *in vivo* imaging target is subject to ongoing studies.

While our manuscript was in preparation, Jiang *et al.* (27) reported overexpression of AMACR by IHC, using a different antibody, in the majority of primary prostate cancers. Although this report did not examine AMACR expression in other tissues, or combine AMACR staining with p63 or evaluate metastatic prostate cancers, the fact that two separate groups simultaneously observe marked overexpression of this protein in primary prostate cancer is a remarkable finding that bolsters the overall importance of AMACR as a new prostate cancer marker.

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Alpha-methylacyl-CoA racemase: a multi-institutional study of a new prostate cancer marker

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Alpha-methylacyl-CoA racemase: a multi-institutional study of a new prostate cancer marker

Aim: To test whether α -methylacyl-CoA racemase (AMACR) is a sensitive and specific marker of prostate cancer.

Methods and results: The expression levels of AMACR mRNA were measured by real-time polymerase chain reaction. A total of 807 prostatic specimens were further examined by immunohistochemistry specific for AMACR. Quantitative immunostaining analyses were carried out by using the ChromaVision Automated Cellular Imaging System and the Ariol SL-50 Imaging System, respectively. AMACR mRNA levels measured in prostatic adenocarcinoma were 55 times higher than those in benign prostate tissue. Of 454 cases of prostatic adenocarcinoma, 441 were positive for AMACR, while 254 of 277 cases of benign prostate

were negative for AMACR. The sensitivity and specificity of AMACR immunodetection of prostatic adenocarcinomas were 97% and 92%, respectively. Both positive and negative predictive values were 95%. By automatic imaging analyses, the AMACR immunostaining intensity and percentage in prostatic adenocarcinomas were also significantly higher than those in benign prostatic tissue (105.9 versus 16.1 for intensity, 45.7% versus 0.02% and 35.03% versus 4.64% for percentage, respectively).

Conclusions: We have demonstrated the promising features of AMACR as a biomarker for prostate cancer in this large series and the potential to develop automated quantitative diagnostic tests.

Keywords: α -methylacyl-CoA racemase, AMACR, biomarker, P504S, prostate cancer

Abbreviations: ACIS, automatic cellular imaging system; AMACR, α -methylacyl-CoA racemase; PIN, prostatic intraepithelial neoplasia; PSA, prostate specific antigen

Introduction

Considerable effort has been made to identify prostate cancer markers, which may be valuable in the early diagnosis, staging, therapeutic monitoring, post-thera-

peutic follow-up and targeted treatment of prostate cancer. Currently, prostate specific antigen (PSA) is the most commonly used biomarker for the diagnosis and the prediction of prognosis of prostate cancer.^{1–3} However, PSA is not a cancer-specific marker, as it is present in both benign and malignant prostatic epithelial cells.⁴ Serum PSA levels are frequently elevated in benign conditions such as benign prostate hyperplasia and prostatitis in addition to prostate cancer.^{5,6} Consequently, patients with elevated serum PSA must

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undergo a biopsy to confirm or exclude the presence of prostate cancer.

The definitive diagnosis of prostate cancer is established by the morphological identification of malignant epithelium in tissue sections. The diagnosis of small foci of prostate cancer on needle biopsy is a major challenge for pathologists because the establishment of a pathological diagnosis requires the presence of a combination of multiple histological features of tumour cells such as an infiltrating pattern, nuclear atypia, and the presence of characteristic extracellular material in malignant epithelium.⁷⁻⁹ No single diagnostic feature of prostatic adenocarcinoma can be used alone reliably. In addition, many benign conditions can mimic the morphology of prostate cancer, despite their benign biological behaviour. Unfortunately, misdiagnosis of prostate cancer may be associated with severe adverse consequences for the patient. Therefore, a biochemical marker specific for prostate cancer would be very useful in clinical practice.

Recent advances in molecular biology have already had a great impact on the clinical practice of medicine. In particular, newly developed techniques such as RNA subtraction hybridization and cDNA microarrays allow the identification and comparison of genes differentially expressed between malignant and benign cells. The application of these new techniques has led to the discovery of *α-methylacyl CoA racemase* (AMACR), also termed P504S, in prostate cancer.¹⁰ AMACR is an enzyme with 382 amino acid residues encoded by a 1621-bp cDNA. Overexpression of AMACR in prostatic adenocarcinoma has recently been reported.¹¹⁻¹³ Two previous studies^{12,13} mostly utilized the small cores of tissue present in tissue microarrays and polyclonal antibodies with weak to moderate protein staining intensity in benign atrophic prostatic glands.¹² Using a monoclonal antibody¹⁰ specific for AMACR, we have shown that AMACR is a good marker for prostate cancer, but the limited number of clinical samples did not allow us to demonstrate its significant clinical utility.¹¹

To investigate more conclusively the clinical importance of this molecular marker, we included a number of expert urological pathologists and analysed the sensitivity and specificity of an immunohistochemical test using a highly specific monoclonal antibody for AMACR in a large number of patients from a variety of geographical locations in the USA. An antibody specific for high-molecular-weight keratins (34BE12), which detects basal cells in benign prostatic glands but is usually non-reactive in prostatic adenocarcinoma,^{14,15} was used for comparison. We also used quantitative real-time polymerase chain reaction (PCR) and two newly developed automated imaging analysis systems:

the ChromaVision Automated Cellular Imaging System (ACIS) and the Ariol SL-50 Imaging System (AriolSL-50), respectively, to compare the mRNA and protein levels of AMACR between benign and neoplastic prostate tissues.

Materials and methods

CASES

Twenty-eight prostate specimens, including 17 with adenocarcinoma and 11 benign prostates, were used for quantitative RNA analysis. Additionally, a total of 807 cases of formalin-fixed paraffin-embedded tissues (Table 1) including prostatic adenocarcinoma (*n* = 454), benign prostatic tissue (*n* = 277) and high-grade prostatic intraepithelial neoplasia (PIN; *n* = 76) were retrieved for conventional haematoxylin and eosin (H-E) staining and immunostaining. All cases were collected between January 2000 and May 2002 and the diagnoses were confirmed by at least two pathologists. The specimens were obtained from five academic medical centres located, respectively, in the East (University of Massachusetts Medical School and Massachusetts General Hospital), Midwest (University of Chicago), South (Veterans Affairs Medical Center, Gainesville, FL) and West (City of Hope National Medical Center, CA) of the USA. The patient ages ranged from 43 to 82 years. The serum PSA levels ranged from 2.1 to 72. The Gleason score ranged from 5 to 10.

QUANTITATIVE REAL-TIME PCR

Fresh tissue was frozen in liquid nitrogen and homogenized with a polytron (Kinematica, Littau-Lucerne, Switzerland). Messenger RNA was extracted using a RNA extraction kit with Trizol reagent (Invitrogen Corp., Carlsbad, CA, USA). Quantitative real-time PCR assay was performed as described previously¹⁶ using

Table 1. Selection of cases

Specimens	No. of cases	Carcinoma	HGPIN	Benign
Prostatectomy	195	178	9	8
Needle biopsy	550	270	62	218
TURP	62	6	5	51
Total	807	454	76	277

HGPIN, High-grade prostatic intraepithelial neoplasia; TURP, transurethral resection of prostate.

300 nm of AMACR forward (5'-GATTTGGCCAGTCA GGAAGC-3') and reverse (5'-GAACACCTGACAAAGCC AAATAGTT-3') primers. PCR was performed on a PE Biosystems GeneAmp 5700 instrument using cDNA reversed-transcribed from RNA of benign and malignant prostate tissues. β -actin was used as an internal reference.

IMMUNOHISTOCHEMISTRY AND IMMUNOFLUORESCENCE

Immunohistochemical studies were performed on 5- μ m sections of formalin-fixed paraffin-embedded tissue by using an avidin-biotinylated peroxidase complex system as previously described.¹¹ The sections were incubated with either a rabbit monoclonal antibody specific for AMACR (P504S; Corixa, Seattle, WA, USA) at a 0.5 μ g/ml dilution or a mouse monoclonal antibody specific for high-molecular-weight cytokeratin (34 β E12, 1 : 50 dilution; Dako, Carpinteria, CA, USA). Diaminobenzidine was used as a chromogen. Double immunostaining was performed with the AMACR and 34 β E12 antibodies, as well as biotinylated secondary IgG sequentially. Diaminobenzidine was used for detection of the AMACR reaction and a different peroxidase substrate, VIP (Vector, Burlingame, CA, USA), which yielded a purple product, was applied for visualizing the reaction of the 34 β E12 antibody. The sections were finally counterstained with methyl green.

Immunofluorescent staining was performed with the AMACR antibody (5 μ g/ml) and the 34 β E12 antibody. Visualization of each localized antibody was achieved by first incubating the sections with 10 μ g/ml anti-rabbit secondary antibody (Vector) conjugated with Texas red followed by an incubation with 10 μ g/ml antimouse secondary antibody (Vector) conjugated with fluorescein (green).

EVALUATION OF THE IMMUNOSTAINING

Six surgical pathologists with extensive experience in prostate pathology from five medical centres in the USA participated in the study. The original morphological diagnosis was generated by each participating pathologist. For each case, both AMACR and 34 β E12 stains were examined. Positive AMACR staining was defined as continuous dark cytoplasmic staining or apical granular staining patterns in cells, which could be easily observed at low-power magnification ($\leq \times 100$). Scant fine granular background staining of epithelial and stromal cells, which could not be seen at low-power magnification ($\leq \times 100$), was considered negative staining.

QUANTITATIVE ANALYSIS OF THE IMMUNOSTAINING

The Automated Cellular Imaging System (ACIS; ChromaVision Medical System Inc., San Juan Capistrano, CA, USA) and Ariol Imaging System (Applied Imaging Corp., Santa Clara, CA, USA) were used to evaluate the immunostaining in prostatic adenocarcinoma compared with adjacent benign prostatic tissue in the same section. Positive staining is calculated by applying two thresholds with one recognizing blue background (haematoxylin stained) cells and another recognizing brown positive cells. The percentage of positivity is the area detected by the brown threshold divided by the sum of the area detected by the brown and blue thresholds. The intensity is calculated by masking out all areas not selected by the brown threshold and calculating the integrated optical density of brown within the remaining area. This value is divided by the area in pixels of the brown mask to calculate an average intensity of a selected area. The values from 60 areas of benign prostatic epithelium and 60 areas of malignant prostatic epithelium were obtained and analysed by using the ChromaVision ACIS. The values from 60 areas including benign prostatic tissue ($n = 24$), prostatic adenocarcinoma ($n = 20$) and high-grade PIN ($n = 16$) were analysed by using the Ariol Imaging System.

STATISTICAL ANALYSIS

The Wilcoxon rank sum test was used to compare scale difference of quantitative real-time PCR and immunostaining results between benign and neoplastic prostate samples.

Results

AMACR mRNA LEVELS MEASURED BY QUANTITATIVE REAL-TIME PCR ANALYSIS

The results of real-time PCR performed to quantitatively assess the expression levels of AMACR mRNA in benign and prostate cancer tissues are shown in Figure 1. The copy number of AMACR was standardized with units of β -actin mRNA measured in the same specimen and expressed as copies/ng β -actin. AMACR mRNA in benign prostate ranged from 191 to 7467 copies/ng β -actin ($n = 11$, mean = 3588), while AMACR mRNA in prostatic adenocarcinoma ranged from 40 799 to 494 465 copies/ng β -actin ($n = 17$, mean = 198 051). The average level of AMACR expression in prostate cancer was 55.2 times ($P < 0.001$) that of benign prostatic tissue.



Figure 1. Quantitative real-time polymerase chain reaction analysis of α -methylacyl-CoA racemase (AMACR) mRNA levels in benign ($n = 11$) and malignant ($n = 17$) prostatic tissues. β -actin mRNA levels were used as an internal control.

AMACR IN BENIGN PROSTATIC TISSUES, HIGH-GRADE PIN AND PROSTATIC ADENOCARCINOMAS

Of 454 prostatic adenocarcinomas, 441 (97%) were positive for AMACR (Figure 2A,B) including those with Gleason score 5 (23/24, 96%), Gleason score 6 (244/250, 98%), Gleason score 7 (105/107, 98%), and Gleason score ≥ 8 (69/73, 95%). The AMACR-positive rates in different Gleason scores (Table 2) were not significantly different. In addition, AMACR was

also positive in 67 of 76 cases (88%) of high-grade PIN (Figure 2C). High-grade PIN displayed patchy basal cells (Figure 2C), while all 454 prostate cancer cases showed non-reactivity for the basal cell marker 34 β E12 (Figure 2B,D).

To determine the specificity of the AMACR test, we analysed its expression in benign prostates. Only 23 out of 277 cases of benign prostate showed detectable levels of AMACR expression by immunohistochemistry. The AMACR immunoreactivity in benign prostatic epithelium was typically weaker and focal. All 277 cases of benign prostatic tissues contained basal cells demonstrated by immunoreactivity for 34 β E12. Particularly important, the benign glands adjacent to the malignant glands were also negative for AMACR and positive for 34 β E12 (Figure 2B–D). Double-labelling methods with either immunoperoxidase staining (Figure 2B,D) or immunofluorescence (Figure 2C) could easily differentiate malignant from benign glands. The expression of AMACR and 34 β E12 appeared mutually exclusive in malignant (positive for AMACR, negative for 34 β E12) or benign prostatic tissues (negative for AMACR, positive for 34 β E12). Most high-grade PIN glands (88% of cases) were reactive for both AMACR and 34 β E12 (Figure 2C).

The AMACR immunohistochemical assay had an overall sensitivity of 97%, a specificity of 92%, a positive predictive value of 95% and a negative predictive value of 95%. The sensitivities varied from 96% to 100% (Centre A, 97%; Centre B, 97%; Centre C, 96%; Centre D, 100%; Centre E, 98%).

QUANTIFICATION OF AMACR IMMUNOREACTIVITY IN BENIGN AND NEOPLASTIC PROSTATIC TISSUES BY AUTOMATIC IMAGING SYSTEMS

As measured by the ACIS, the average percentage of AMACR-positive staining was 45.7% in prostatic carcinomas and 0.02% in benign prostatic tissues ($P < 0.001$). The average intensity of AMACR-positive cells was 105.9 in prostatic carcinoma and 16.1 in benign prostatic tissues ($P < 0.02$, Figure 3). While using another automatic system, the Ariol SL-50, the mean percentages of AMACR immunostaining were 4.64 (ranging from 0 to 24.51) in benign prostatic tissue, 21.84 (ranging from 2.69 to 57.66) in high-grade PIN, and 35.03 (ranging from 6.22 to 78.64) in prostatic adenocarcinomas. The differences are statistically significant ($P < 0.001$).

Discussion

Recent advances in molecular biology have been translated into significant progress in clinical medicine.

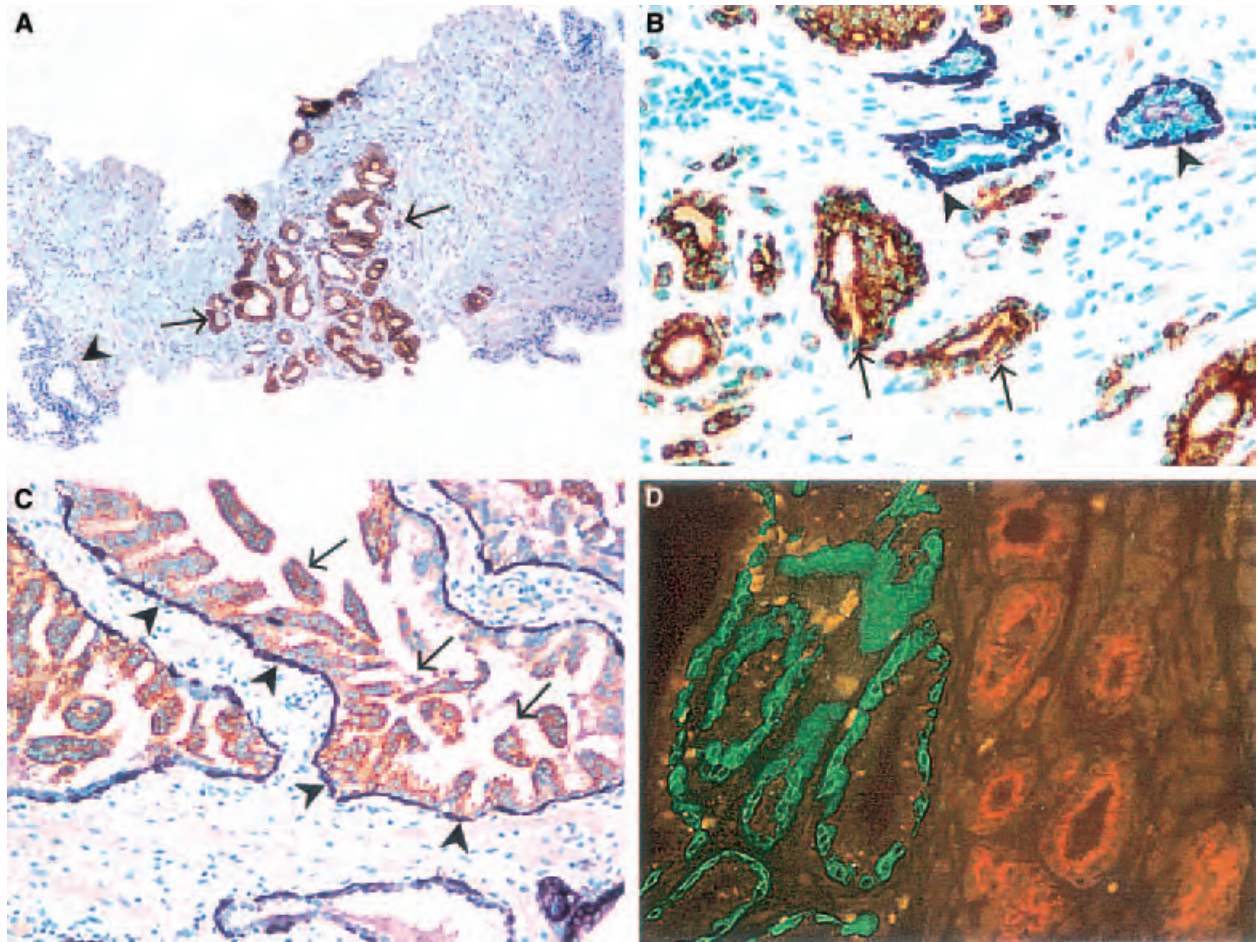


Figure 2. A, α -methylacyl-CoA racemase (AMACR) immunostaining on a needle biopsy core showing small focus of prostatic adenocarcinoma (arrows) with intense, continuous, granular cytoplasmic (brown) staining and no AMACR staining in adjacent benign glands (arrowheads). B, Double immunostaining on prostatic tissue showing prostatic adenocarcinoma with brown AMACR staining (arrows) and benign glands with blue-purple basal cell (34 β E12) staining (arrowheads). C, Double immunostaining on prostatic tissue showing high-grade prostatic intraepithelial neoplasia with both brown AMACR staining in neoplastic cells (arrows) and discontinuous blue-purple staining in basal cells (arrowheads). D, Immunofluorescence of prostatic tissue showing benign glands (left) stained with the 34 β E12 antibody labelled with fluorescence (green) and prostatic adenocarcinoma (right) stained with the AMACR antibody labelled with Texas red (orange).

Table 2. Expression of α -methylacyl-CoA racemase in prostatic adenocarcinoma

Gleason score	No. of cases	Positive	Negative	Positive rate, %
5	24	23	1	96
6	250	244	6	98
7	107	105	2	98
≥ 8	73	69	4	95
Total	454	441	13	97

One of the most powerful new techniques is genetic profiling using microarray (gene chip) technology.¹⁷⁻¹⁹ However, despite the detection of many prostate cancer markers discovered by microarrays, very few if any have been used in clinical practice. In this study, we tested the hypothesis that AMACR is a biomarker for prostate cancer. Our study of AMACR in 807 cases of benign and malignant prostatic diseases from five different medical institutions has demonstrated the promising potential of AMACR as a marker for prostate cancer. The quantitative analyses of AMACR mRNA and protein expression levels further strengthen the findings. AMACR may be the first gene identified from prostate cancer by cDNA microarrays to be suitable for

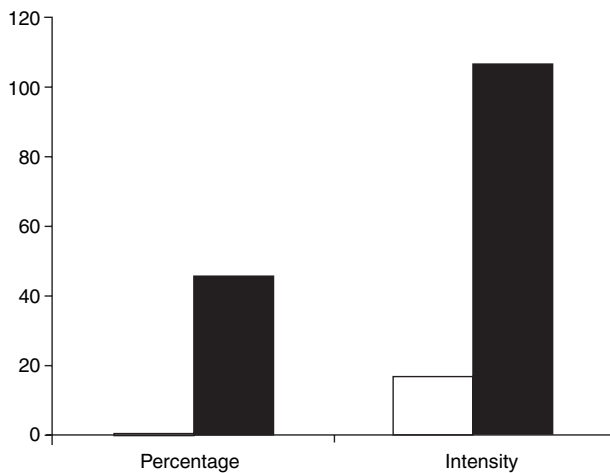


Figure 3. Comparison of the percentage and intensity of α -methylacyl-CoA racemase immunostaining between benign (□) and malignant (■) prostatic tissues analysed by ChromaVision Automated Cellular Imaging System.

clinical practice and potentially improve the diagnosis and treatment of prostate cancer.

The wide use of serum PSA screening has resulted in an increased detection of patients with prostate cancer. A tissue diagnosis (prostate needle biopsy or transurethral resection of prostate) is mandatory for a patient with prostate cancer to receive appropriate therapy to minimize morbidity and mortality. However, tissue diagnosis can be difficult and inaccurate if the cancer is very limited. Over-diagnosis (false positivity) may cause unnecessary treatment of men without prostate cancer and lead to incontinence or impotence. Under-diagnosis (false negativity) may delay effective treatment to patients with prostate cancer and may lead to recognition of disease at a more advanced stage. Unfortunately, there is a significant error rate in pathological diagnosis of prostate cancer in general practice because discrimination between benign and malignant glands can be difficult in a small biopsy specimen and this can be even more difficult for pathologists who are not specialized in urological pathology. A recent study comparing the diagnoses of general pathologists and an expert urological pathologist in 224 prostate needle biopsies has shown a misdiagnosis rate of prostate needle biopsy of 12.3%.²⁰ If the significant error rate of prostate biopsies is even only 1% of the approximately one million prostate needle biopsies performed each year in the USA, 10 000 cases could be misdiagnosed. Considering the large number of prostate needle biopsies performed in the USA and around the world each year, this error rate is alarming and could have a

significant health and economic impact. The accuracy of pathological diagnosis of prostate cancer could be improved by the application of a more objective and reliable specific marker for prostatic cancer cells.

AMACR displays several attractive features for a prostate cancer marker, first, with significant levels of overexpression, including 55-fold of mRNA levels by real-time PCR and 34-fold of protein levels by Western blotting,¹¹ 6.6-fold (ACIS intensity), 7.5-fold (Ariol SL-50%) and 2285-fold (ACIS percentage). AMACR is one of the few genes consistently detected in prostate cancer cells by conventional methods such as immunohistochemistry or immunofluorescence in paraffin-embedded tissue specimens. Our study showed that 441 of 454 cases (97%) of routine prostatic adenocarcinoma specimens were positive in an AMACR assay. The positive predictive value is 95%. In this study, we deployed two newly developed automatic imaging systems. Automatic imaging analysis, still in its early phase of development, allows more accurate and objective measurement of immunoreactivity instead of relatively primitive 1+, 2+ and 3+ quantification. These analyses all demonstrated a significant difference between benign prostates and prostate cancer, although the conditions of these systems remain to be perfected.

Second, AMACR is a marker with high specificity for prostate adenocarcinoma. In contrast to carcinoma, most benign cases and the benign prostate tissue adjacent to carcinoma were negative for AMACR. The negative predictive value is 95%. Some benign prostatic conditions mimicking cancer including atrophy, basal cell hyperplasia and inflammatory glands can be easily distinguished from prostate cancer by their non-detectable AMACR. Other previously identified markers such as P503S and P510S may have only limited clinical utility because they are present in both benign and malignant prostatic epithelia.¹⁰

Finally, AMACR is present in different grades of prostate cancer. Another prostate cancer marker, hepsin, also recently identified by microarrays,^{21,22} may have promising clinical utility. However, the hepsin expression level is significantly decreased in high-grade prostate cancer.²³

Recently, elevated AMACR expression has been reported in a smaller percentage of precursor lesions of prostate cancer, including atypical adenomatous hyperplasia²⁴ as well as high-grade PIN,^{11–13} suggesting a role for AMACR at an earlier phase of prostatic carcinogenesis. Further functional and biochemical analysis of AMACR may provide insights into the basis of the development of prostate cancer and potentially lead to preventive measures. Additionally, both high-

grade PIN and atypical adenomatous hyperplasia retain basal cells that can be demonstrated by 34 β E12 immunostaining. Therefore, it is easy to distinguish high-grade PIN and atypical adenomatous hyperplasia from malignant glands with the combination of staining for AMACR and basal cell markers.

The differences between cancer and benign glands can be accentuated by double immunostaining methods. With available specific antibodies and current techniques, we were able to show for the first time two distinct colours between malignant (brown or red) and benign (blue or green) epithelia of the prostate (Figure 2B,D) in conventional paraffin-embedded tissue specimens. Although these methods are unlikely to replace the conventional H-E stain for pathological evaluation of slides, our results using double immunostaining and the ChromaVision ACIS may provide the basis for an automated screening test for prostate cancer. There may be broader applications for AMACR in the diagnosis and treatment of prostate cancer. In contrast to PSA, AMACR is relatively specific for prostate cancer. An antibody-based or PCR-based serum or seminal fluid test for AMACR is unlikely to be affected by benign prostatic diseases. In addition, if an AMACR antibody is conjugated with a fluorescent or radioactive indicator, the uptake and binding of AMACR antibody by prostate cancer cells may delineate the entire tumour and provide preoperative information about tumour volume for primary or metastatic prostate cancer. Finally, an AMACR antibody may be used to target prostate cancer or deliver therapeutic agents locally for treatment of prostate cancer.

Epidemiological and animal studies have shown an association between dietary factors and increased risk for prostate cancer.^{25,26} Although increased fat content has been observed in prostate cancer cells, the molecular mechanism of this association is unclear. AMACR, an essential enzyme for the degradation of branched-chain fatty acids by β -oxidation, catalyses the conversion of several (2R)-methyl-branched-chain fatty acyl-CoAs to their (S)-stereoisomers.²⁷ High levels of branched chain fatty acids have been found in some dietary sources such as beef, milk and dairy products. Accumulation of branched chain fatty acids in prostatic epithelium may lead to increased levels of AMACR. The discovery of AMACR overexpression in prostate cancer suggests a link between AMACR and dietary fat in the development of prostate cancer. The mechanism of AMACR in prostatic carcinogenesis should be further investigated.

In summary, this is the first multi-institutional study to evaluate the potential clinical application of

α -methylacyl-CoA racemase in the diagnosis of prostate cancer. By using conventional immunohistochemical analysis and a number of quantitative analyses, we have demonstrated that α -methylacyl-CoA racemase is an excellent biochemical maker of prostate cancer with high sensitivity and specificity. The potential to develop enhanced and novel diagnostic and treatment methods of prostate cancer using this maker is promising.

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