Osteopontin: Possible Role in Prostate Cancer Progression


Urology Research and Gene Therapy Laboratory, Departments of Urology [G. N. T., I. K., U. E. S.] and Pathology [R. M.], University of Berne, CH-3010 Berne, Switzerland; Molecular Urology and Therapeutics, Department of Urology, University of Virginia Health Science Center, Charlottesville, Virginia 22908 [R. A. S., L. W. K. C.]; and Basic Sciences, Dental Branch, University of Texas Health Science Center, Houston, Texas 77030 [R. E. D., J. A. K., C. M. F. C.]

ABSTRACT

Human prostate cancer has the propensity to metastasize to the bone where reciprocal cellular interactions between prostate cancer and bone cells are known to occur. Osteopontin (OPN), a noncollagenous bone extracellular matrix, is a secreted adhesive glycoprotein with a functional RGD cell-binding domain that interacts with the αb3 cell surface integrin heterodimer. OPN has been associated with malignant transformation as well as being ligand to the CD44 receptor. Polyclonal antibodies to human OPN (hOPN) were prepared, and specificity was shown by pre-absorption with recombinant hOPN. The stimulatory effect of hOPN protein and the inhibitory effect of hOPN antibody on human prostate cancer cell lines LNCaP and C4-2 were assessed by induction or inhibition of anchorage-independent growth, respectively. Expression of hOPN mRNA in prostate cancer cell lines and human prostate cancer tissue specimens were measured by mRNA blot analysis. Protein expression was assessed by immunohistochemistry in human prostate cancer specimens and by Western blot analysis in prostate cancer cell lines. hOPN stimulated anchorage-independent growth of the human prostate cancer cell lines LNCaP and C4-2 in vitro. Antibodies to hOPN inhibited the growth-stimulatory effect by endogenous OPN, which can be overcome by the addition of exogenous hOPN. hOPN mRNA and protein are expressed in human prostate cancer cell lines in vitro and in clinical human prostate cancer specimens. These findings taken together suggest that OPN may act as a paracrine and autocrine mediator of prostate cancer growth and progression.

INTRODUCTION

After an initial responsiveness to hormonal deprivation, advanced prostate cancer almost invariably relapses, and androgen-independent clones progress and metastasize nonrandomly to the axial skeleton. Experimental studies of human prostate cancer models have stressed the influence of the mesenchymal-epithelial interaction on the development of prostate cancer (1). In a series of studies, we observed that prostate and bone fibroblasts, in the appropriate host hormonal milieu, can induce the progression of prostate cancer cells from an androgen-dependent to an androgen-independent state, whereby cells with the latter phenotype express osseous metastatic potential (2, 3). It has been suggested that the development of osseous metastasis is dependent upon bone marrow and osteoblast-derived soluble growth factors that stimulate the growth of prostate cancer cells in a paracrine-mediated manner (4, 5).

Extracellular matrix has been demonstrated to play a critical role in tumor cell growth, adhesion, migration, and metastasis. Although the role of the extracellular matrix and its intracellular signaling through integrin heterodimers remain to be defined, interactions between bone matrix proteins and prostate cancer cells are likely to be the key determinants regulating prostate tumor cell behavior. The expression of bone matrix proteins is not restricted to bone tissue. One of these noncollagenous bone matrix proteins, OPN, a highly posttranslationally modified glycoprotein, contains the cell attachment amino acid sequence RGD (arginine-glycine-aspartic acid), which binds to the αvβ3 integrin heterodimer (6, 7). In the bone, osteoclast activity is increased as a consequence of the interaction between OPN and the osteoclast cell surface integrins. OPN is also involved in regulating bone formation and remodeling of mineralized tissues. OPN demonstrates multiple interactions with Ca2+. Furthermore, OPN recruits and stimulates macrophages and lymphocytes as part of a nonspecific response to microbial infections, inhibits and disrupts the growth of calcium oxalate crystals, affects nitric oxide production, and is involved in mediating cell migration (8, 9). Recently, OPN has been reported to be a ligand of the CD44 receptor (10).

OPN has been shown to be overexpressed in human cancers (11–13), and OPN overexpression confers malignant transformation and was observed frequently in a variety of tumorigenic human cell lines (12–14). Consistent with these observations, serum levels of OPN were substantially elevated in patients with metastatic cancer (15). Ha-ras-transfected NIH 3T3 cells overexpress OPN and show increased cell motility in vitro and in vivo (16). A variety of OPN expression vectors have been constructed, and OPN expression in NIH 3T3 cells is associated with increased anchorage-independent cell growth in vitro and in vivo (17). OPN-expressing NIH 3T3 cells form subcutaneous tumors in nude mice, indicating that OPN enhances tumorigenic potential of NIH 3T3 cells (18). Recent studies have shown that OPN expression in NIH 3T3 cells is associated with increased angiogenesis in vivo (19). These findings suggest that OPN may act as a paracrine and autocrine mediator of prostate cancer growth and progression.

Received 12/7/98; revised 5/24/99; accepted 6/4/99.

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

1 This work was supported by Swiss National Science Foundation Grant 32-43326.95 (to G. N. T.), NIH Grant AR39273 (to C. M. F. C.), and Public Health Service Grants CA-63341 and CA-64863 (to L. W. K. C.).

2 To whom requests for reprints should be addressed, at Department of Urology, Anna-Seiler-Haus, Inselspital, CH-3010 Bern, Switzerland. Phone: 41-31-632-36-41; Fax: 41-31-632-21-80.

3 Present address: Department of Biological Sciences, University of Delaware, Newark, DE 19716.
Role of Osteopontin in Prostate Cancer Progression

Progression and dissemination of prostate cancer (18). We previously reported, in a preliminary finding on the potential role of bone matrix proteins such as OPN, on the progression and dissemination of prostate cancer (18).

In this communication, we have extended our previous report on the potential role of bone matrix proteins such as OPN on the progression and dissemination of prostate cancer. We have evaluated the role of OPN in human prostate cancer progression and metastasis. We have demonstrated the value of characterizing in detail the phenotypic and genotypic alterations in LNCap lineage-related cell models of prostate cancer progression and their utility to define clinical prostate cancer. Herein we provide the experimental evidence that OPN over-expression is associated with human prostate cancer progression. We conclude that OPN may confer selective growth and malignant potential to prostate tumor cells in situ.

MATERIALS AND METHODS

Cell Culture. LNCap cells, passage 29 of the original line developed by Horoszewicz et al. (19), were kindly supplied by Dr. Gary Miller (University of Colorado, Denver, CO). LNCap cells (passages 37–40), C4–2 cells (passages 20–23), and NbE 1.4 cells (passages 30–35) were grown in T-medium containing normal prostate cancer, BPH, high-grade PIN, and prostate cancer were cut and used for immunohistochemical staining. Thirty-one radical prostatectomy specimens and 8 pTURP specimens were evaluated. Tumor tissue samples for RNA blot analysis were resected and snap frozen from radical prostatectomy specimens by the pathologist. BPH and tumor tissues from TURP or pTURP were immediately snap frozen. Normal prostate tissues were obtained from organ donors according to the institutional guidelines and with approval of the University Ethical Committee. All tissues were stored at −80°C until further processing.

Immunohistochemical Staining of OPN. Immunohistochemical staining was performed on deparaffinized human prostate cancer tissue sections. Specimens were washed three times in PBS, preincubated with donkey serum 1:20 to block nonspecific activity, and then incubated with an affinity column-purified, polyclonal, goat-specific primary antibody against hOPN. The specificity of the hOPN antibody was tested by preabsorption of column chromatographically purified hOPN before immunostaining of a positive control (human bone tissue; Fig. 3, a and b). Preimmunization serum of the same animal was used as a negative control for hOPN, and human bone tissue sections served as positive control. After 3 × PBS wash preincubation with donkey serum 1:20, the tissue specimen was incubated with the secondary antibody donkey anti-goat (alkaline phosphatase) 1:50. After three PBS washes, the alkaline phosphatase substrate (Vector Red; Vector Laboratories, Inc., Burlingame, CA) was added, incubated, and washed. Slides were then stained in filtered hematoxylin, dehydrated (80% ethanol, 95% ethanol, absolute ethanol, and xylene), and mounted with Permount (Fisher Scientific Corp., Fair Lawn, NJ). Although immunostaining for OPN in cultured prostatic cancer cell lines was uniform, multifocal OPN staining was commonly observed in clinical specimens with multifocal disease. Staining for OPN was rated as follows: −, negative staining; (+), slight staining; +, positive focal staining; and ++, strong focal staining. Only positive and strong focal staining were considered as positive staining for OPN.

Soft Agar Colony Formation. To determine the ability of hOPN to stimulate colony formation in LNCap and C4–2 cells when grown in vitro, TCM, a defined serum complement (Celox Co., Minnetonka, MN, see Ref. 1) and CM from NIH 3T3 fibroblasts (negative control) were used as baseline. Cells (2.5 × 10^4 LNCap) and 1.0 × 10^5 (high density) C4–2 cells were trypsinized to single-cell suspensions and incubated for 4 h either with 3T3 CM, hOPN (10 μg/ml), purified hOPN antibody (dilution 1:50), preimmunization control serum, or in combination (OPN 1 μg/ml plus OPN-antibody; dilution, 1:50) after treatment with 0.02% EDTA. The concentrations for OPN (10 μg) and OPN-antibody (dilution, 1:50) were determined in preliminary experiments.

3T3 CM was prepared as follows. Cells in 70–80% confluent culture were downshifted to serum-free T-medium containing 2% TCM, a serum-free defined medium supplement only. After 48 h, 3T3 CM was removed and lyophilized, and protein concentrations in the CM were determined using a protein assay (Bio-Rad Laboratories, Richmond, CA); they ranged from 70–
100% of control (T-medium and 2% TCM; 1.3 mg/ml). Samples were then reconstituted in T-medium to 2× concentration and then filtered (0.2 μm; Nalge Co., Rochester, NY).

After incubation with EDTA, MgCl₂ and CaCl₂ were supplemented, and the cells were resuspended in 0.3% agarose containing T-medium supplemented with 2% TCM and plated on a 12-well plate (Costar, Cambridge, MA) containing 0.6% agarose as a bottom layer. The cover layer, consisting of T-medium and 2% TCM, was changed weekly. Colonies larger than 0.1 mm were scored 4–6 weeks after plating.

**RNA Blot Analysis.** Total cellular RNA was extracted from cells (LNCaP, C4–2, DU145, PC-3, NbE1.4, and 3T3) and from snap frozen, pestle-ground human tissue samples by the RNAzolB method (Biotech Laboratories, Inc., Houston, TX.), a single step purification protocol. Thirty μg of RNA, as determined by absorbency at 260 nm, were subjected to RNA blot analysis by electrophoresis in a 0.9% agarose gel containing 2 M formaldehyde. RNAs were transferred by capillary blotting onto Zetaprobe membrane (Bio-Rad, Richmond, Calif.) using 1× TAE buffer. RNAs were cross-linked to the membranes by UV exposure using a stratalinker (Stratagene, La Jolla, Calif.) at 1500 mJ and prehybridized in hybridization buffer (10% dextran sulfate, 1% SSC, 1 m NaCl, and 20 μg/ml salmon sperm DNA from Amersham, Inc., Arlington Hts. IL). The solution hybridization was performed by incubation at 65°C overnight by exposing the membranes to a 3²P-labeled OPN or GAPDH cDNA (loading control) probe, having specific activity >1 × 10⁸ dpm/μg. After hybridization, the membranes were washed in 2× SSC at room temperature for 30 min, then washed under highly stringent conditions (twice for 30 min in 2× SSC/1% SDS, then once for 30 min in 0.5× SSC/1% SDS) at 65°C. Autoradiograms were prepared by exposing Kodak X-Omat AR films to the membrane at −80°C with intensifying screens. Autoradiograms of RNA blot analysis for OPN and GAPDH were analyzed, and OPN values were normalized to GAPDH by means of an AMBIS Molecular Dynamics Imaging System (Molecular Dynamics, Sunnyvale, CA).

**Western Blot Analysis.** Recombinant hOPN (20 μg) and cell lysate samples (20 μg) were run on 10% SDS-polyacrylamide gels and transferred onto nitrocellulose paper by electrophoresis. After blocking with PBST (PBS with 0.1% Tween 20), the blots were incubated with the indicated primary antibody (hOPN-AB) at a dilution of 1:250 at 4°C for 12 h. The blots were then washed three times with PBST buffer and incubated with the secondary streptavidin peroxidase-conjugated antibody for 1 h at room temperature. After being washed three times, the protein bands were detected by enhanced chemiluminescence (Amersham, Inc.).

**Intracellular Quantification of OPN by Flow Cytometry.** Cells (1 × 10⁶) were harvested and washed with 1× PBS and then fixed with 2% paraformaldehyde at 4°C for 30 min. After fixation, cells were washed twice in ice cold permeabilization buffer [PB: PBS (pH 7.4), 0.1% saponin, and 0.1% BSA] and incubated with goat anti-OPN antibody at 1:250 dilution. The normal control antibody is defined as 1.0. Upon the addition of OPN antibody, the mean channel fluorescence shifted to the right, an indication of increased fluorescence intensity. The ratios were calculated and represent a semiquantitative estimation of OPN protein content in the cells.

**Statistical Analysis.** For statistical analysis of soft agar colony-forming activity, a one-sided Student’s t test with unequal variances was used (SPSS).

**RESULTS**

RNA blot analysis of several human prostate cancer epithelial cell lines (Fig. 1a) revealed an elevated expression of OPN mRNA in androgen-independent and tumorigenic cell lines C4–2, DU145, and PC-3 and to a lesser extent in the androgen-dependent LNCaP cell line (Fig. 1a). The normal
Role of Osteopontin in Prostate Cancer Progression

C4–2, DU145, and PC3 express OPN protein on their surface with the hOPN antibody demonstrated that the cell lines LNCaP, C4–2, DU145, and PC3 express OPN protein on their surface (Fig. 1c). Western blot analysis confirmed these findings (data not shown).

Because conditioned media collected from bone fibroblasts stimulated human prostate cancer growth in vivo (22), we examined further whether osteopontin may support the anchorage-independent growth (soft agar colony formation of prostate epithelial cells) in vitro because this activity correlates closely with tumorigenicity of target epithelial cells in vivo (23). hOPN (10 μg/ml) stimulated the anchorage-independent growth of androgen-dependent LNCaP cells in a soft agar colony formation assay (P = 0.013; Fig. 2a). hOPN antibody did not significantly alter soft agar colony-forming activity. hOPN added in excess (200 μg/ml) could overcome hOPN antibody inhibition. The addition of CM derived from NIH3T3 cells did not significantly stimulate the anchorage-independent growth of the LNCaP cells (baseline level was defined by the addition of a serum-free supplement, 2% TCM).

Similar findings were demonstrated in the androgen-independent C4–2 cells (Fig. 2b) at low density (1.0 × 10³ cells); hOPN (10 μg/ml) induced anchorage-independent growth (P < 0.01). Unlike LNCaP cells, hOPN antibody alone decreased the baseline number of soft agar colonies formed by C4–2 cells below baseline (P = 0.038), and again this inhibition could be overcome by exogenously added hOPN (200 μg/ml). At a higher density (5.0 × 10³ cells), androgen-independent C4–2 cells demonstrated an elevated intrinsic anchorage-independent growth at baseline. Under these autocrine stimulatory conditions, hOPN did not significantly stimulate anchorage-independent growth, but the addition of hOPN antibody inhibited this intrinsic androgen-independent growth (data not shown). Again, the hOPN antibody inhibition could be overcome by exogenous hOPN (data not shown). The preimmune serum of the same animal did not inhibit anchorage-independent growth in preliminary experiments (data not shown).

To demonstrate the presence of OPN in human tissues, we conducted immunohistochemical analysis of clinical specimens of prostate cancers obtained from radical prostatectomy and transurethral resections. As a positive control and to demonstrate the specificity of the hOPN antibody, we stained normal human bone for OPN (Fig. 3a), which exhibited distinct staining of the reversal lines and osteocytes. Preabsorption of the hOPN antibody with affinity-purified hOPN abolished the immunostaining (Fig. 3b). Immunohistochemical staining of pathologically normal human prostate showed no immunostaining or only slight staining of the luminal surface of atrophic glands, a result in agreement with the lack of OPN in a normal rat prostatic epithelial cell line, NbE-1.4. Prostate cancer showed low staining intensity in low Gleason grade prostate cancer (Fig. 3c) and more intense immunostaining in high Gleason grade (Fig. 3d) and androgen-independent prostate cancer (Fig. 3e). BPH did not stain positive for hOPN antibody (Fig. 3f), which is in contrast to the mRNA blot analysis. BPH often has an inflammatory component that is associated with macrophages, which stain strongly positive for OPN, as shown in this TURP specimen (Fig. 3g). The results of the 39 prostate tumors are summarized in Table 1.

Fifty-eight % (18 of 31) of the peripheral zone prostate cancers from radical prostatectomy specimens with a Gleason score 6 and higher stained positive for OPN, with a more intense staining in high-grade tumors. Three of four (75%) transitional zone cancers stained positively for OPN, and two of eight (25%) of the prostate cancer specimens obtained from palliative transurethral resection stained positively for OPN. High-grade PIN stained positive in 4 of 12 (33%) cases. All of the patients (n = 6) with Gleason score 9 prostate cancer showed positive staining for OPN, as did 50, 58, and 67% of patients with Gleason scores 8, 7, and 6, respectively. Fig. 3h shows representative stainings of such OPN-positive tumors.

RNA blot analysis of tumor tissues demonstrated, with few exceptions, that OPN mRNA is widely expressed by prostate
Interestingly, tumor specimens derived from patients with distant metastasis (e.g., lymph node involvement and bone metastasis) showed higher levels of OPN mRNA expression. BPH specimens demonstrated OPN mRNA expression at a lower level.

**DISCUSSION**

OPN, a noncollagenous bone matrix protein, was found to be prevalently expressed by human prostate cancer cell lines and clinical prostate cancer specimens at the levels of both mRNA and protein. OPN also stimulates anchorage-independent growth.
of both androgen-dependent LNCaP and androgen-independent C4–2 human prostate cancer cells in vitro. On the basis of the data from blocking hOPN activity by hOPN antibody, it is conceivable that OPN may be one of the active extracellular matrix components that contribute to anchorage-independent growth of human prostate cancer cells in vitro. Although presently it is not known how OPN may induce anchorage-independent growth of prostate cancer cells, interaction between OPN and its cell surface receptor αvβ3 integrin isotype in cancer cells has been observed to transduce cell-matrix signaling that culminates in increased cell motility, invasion, angiogenesis, and the ability to proliferate under anchorage-independent conditions (24). In addition, the role of CD44 receptors in the mediation of metastatic processes via OPN remains to be determined (25).

Prostate cancer cells commonly adhere to and proliferate in bone. These events are characterized by the induction of an osteoblastic reaction in the axial skeleton. The mechanisms underlying this preferential homing to the bone are unclear. Experimental data support several proposed mechanisms. For example, bone-derived growth factors have been identified and appear to play a key role in augmenting prostate cancer cell proliferation in the skeleton (1, 5). OPN has been shown in a previous study to recruit a quiescent human prostate epithelial cell population into proliferative phase (26). OPN could also alter the tumor microenvironment and for example alter the local nitric oxide production by macrophages to favor tumor growth and androgen-independent progression. These results are expanded in the present study, where OPN may be the major soluble factor secreted by osteoblasts as well as prostate cancer cells that accounts for stimulated anchorage-independent growth of prostate cancer cells in vitro. In addition to OPN overexpression by prostate cancer cells, several other skeletal and matrix-associated proteins, such as bone morphogenetic proteins 2, 3, and 4 (27) and bone sialoprotein (28), are also expressed by prostate cancer cells. It is conceivable that overexpressed skeletal and bone matrix-associated proteins may allow prostate cancer cells to gain adhesive, growth, and survival advantages that eventually progress to become androgen independent and metastatic with a predilection for spreading to the bone. In support of this concept, we observed for the first time that clinical prostate tumor specimens of high Gleason grade or metastatic specimens expressed high levels of OPN. Our results also support the notion that cultured prostate cancer cell lines with cell lineage relationship, such as LNCaP and C4–2 cells, provide efficient and reliable means to detect biomarkers, such as OPN, that may be associated with human prostate cancer progression.

In summary, OPN mRNA and protein are expressed in prostate cancer cell lines and human prostate cancer specimens. The malignant and metastatic phenotype seems to be correlated with elevated OPN expression. These findings suggest a paracrine and autocrine role of OPN in prostate cancer growth, invasion, and metastasis.

REFERENCES


Osteopontin: Possible Role in Prostate Cancer Progression

George N. Thalmann, R. A. Sikes, R. E. Devoll, et al.