Androgen-Independent Growth and Tumorigenesis of Prostate Cancer Cells Are Enhanced by the Presence of PKA-Differentiated Neuroendocrine Cells

Paul D. Deeble,1,3 Michael E. Cox,4 Henry F. Frierson, Jr.,2 Robert A. Sikes,5 Jodie B. Palmer,4 Robert J. Davidson,1 Eli V. Casarez,1 George P. Amorino,1 and Sarah J. Parsons1

Departments of 1Microbiology and Cancer Center and 2Department of Pathology, University of Virginia Health System, Charlottesville, Virginia; Biology Department, Mary Baldwin College, Staunton, Virginia; 3The Prostate Center at Vancouver General Hospital, University of British Columbia, Vancouver, British Columbia, Canada; and 4Laboratory for Cancer Ontogeny and Therapeutics, Department of Biological Sciences, University of Delaware, Newark, Delaware

Abstract

The neuroendocrine status of prostatic adenocarcinomas is considered a prognostic indicator for development of aggressive, androgen-independent disease. Neuroendocrine-like cells are thought to function by providing growth and survival signals to surrounding tumor cells, particularly following androgen ablation therapy. To test this hypothesis directly, LNCaP cells were engineered to inducibly express a constitutively activated form of the cyclic AMP–dependent protein kinase A catalytic subunit (caPKA), which was previously found upon transient transfection to be sufficient for acquisition of neuroendocrine-like characteristics and loss of mitotic activity. Clonal cells that inducibly expressed caPKA enhanced the growth of prostate tumor xenografts in vivo, with the greatest effects seen under conditions of androgen deprivation. These results suggest that neuroendocrine-like cells of prostatic tumors have the potential to enhance androgen-independent tumor growth in a paracrine manner, thereby contributing to progression of the disease. [Cancer Res 2007;67(8):3663–72]

Introduction

Neuroendocrine-like cells are found in the normal prostate as well as in benign lesions of the tissue (1–3). However, their numbers increase in neoplastic growths, and their prevalence correlates with tumor size and progression to hormone-resistant states (4–9), suggesting that they may play a role in advancing the disease. A large number of clinical studies have shown that prostatic neuroendocrine-like cells and their associated markers serve as prognostic indicators of poor patient survival (10–16), providing further support for a functional link between neuroendocrine-like cells and tumor progression.

Existing evidence supports a model in which neuroendocrine-like cells arise from within prostate tumors following tumor cell exposure to one or more differentiation factors (2, 6, 17). LNCaP cells acquire neuroendocrine characteristics in response to agents that increase intracellular cyclic AMP (cAMP) levels, including forskolin or epinephrine (18, 19), long-term androgen ablation (20, 21), and, to a lesser extent, cytokines (22–24). An array of neuroendocrine-specific markers, including S-100, chromogranin A (CgA), and neuron-specific enolase (NSE; ref. 25), is up-regulated in response to these agents. Long-term androgen ablation therapy or castration has also been found to enrich neuroendocrine-like populations within human tumors or xenografts in nude mice, respectively (26–28). Based upon these and other studies, we postulated that cAMP-mediated signaling might be a primary pathway of neuroendocrine differentiation in vivo.

Neuroendocrine-like cells in tumors, while themselves nonmitotic, have been found to correlate with increased proliferative activity of adjacent carcinoma cells (4, 17) and to produce neurosecretory growth and survival factors (19, 28–30) that could contribute to the progression of late-stage prostate cancer during aggressive therapy. However, the causal relationship between nondividing, neuroendocrine-like cells within tumors and tumor progression has not been rigorously tested, in part, because the differentiation process is reversible and requires that the differentiating agent(s) be continuously present (19). A logical molecular candidate to replace extracellular differentiation factors was the major intracellular effector of cAMP, cAMP-dependent protein kinase A (PKA). In fact, the generation of neuroendocrine-like cells by cAMP-activating agonists was found to be dependent on PKA (24). In the current study, tetracycline-regulated expression of a constitutively activated form of PKA was found to enhance neuroendocrine-like differentiation of prostate tumor cells as measured by loss of mitotic activity, gain of neuroendocrine-like morphologic characteristics, and secretion of neuropeptides. Most importantly, when cocultured in vitro or coinjected into nude mice with prostate tumor cells, these PKA-differentiated neuroendocrine-like cells enhanced anchorage-dependent and anchorage-independent growth and tumorigenicity of the tumor cells, with the most pronounced effects being observed under conditions of androgen deprivation. These results are supportive of the hypothesis that neuroendocrine-like cells of prostate cancer contribute to disease progression by providing growth and survival factors to surrounding cancer cells. The findings also reveal potential new sites of therapeutic intervention (i.e., signaling pathways that regulate neuroendocrine differentiation and growth of tumor cells activated by neuropeptides).

Requests for reprints: Sarah J. Parsons, Department of Microbiology, University of Virginia Health System, P.O. Box 800734, Charlottesville, VA 22908-0734. Phone: 434-924-2352; Fax: 434-982-0689; E-mail: sap@virginia.edu.

doi:10.1158/0008-5472.CAN-06-2616

www.aacrjournals.org 3663 Cancer Res 2007; 67: (8). April 15, 2007
Materials and Methods

**Cell culture.** LNCaP cell lines (from Dr. I.W. Chung, Emory University) were grown in T-Medium supplemented with 5% fetal bovine serum (FBS; Life Technologies, Gaithersburg, MD) and penicillin/streptomycin, unless otherwise indicated, and maintained at 37°C in a humidified, 5% CO₂ environment (31). PC3 cells (American Type Culture Collection, Rockville, MD) were grown in DMEM (Life Technologies) with 10% FBS and penicillin/streptomycin.

**Constructs.** To generate a tetracycline-inducible expression vector for the constitutively active cPA catalytic subunit (caCqr), the pTRE plasmid (Clontech, Palo Alto, CA) was first digested with EcoRI-BamHI to insert a linker containing EcoRI, EcoRV, XbaI, BglII, XhoI, HpaI, and BamHI sites, yielding pTRE-L. FLAG-tagged caCqr was then inserted into pTRE-L as an XbaI-HpaI fragment from an intermediate vector to generate pTRE-FLAG caCqr. Original cloning of caCqr was accomplished by PCR amplification of a XbaI-HpaI fragment from the MT Cqr-neo plasmid (kindly provided by Dr. G.S. McKnight, University of Washington, Seattle, WA).

**Derivation of Tet-inducible cell lines.** LNCaP cells inducibly expressing FLAG caCqr were derived according to the manufacturer's instructions using the pTRE-FLAG caCqr plasmid (Clontech). Positive clones were assessed by Western immunoblotting and immunofluorescence, subcloned by limiting dilution, and maintained in growth medium plus 600 μg/mL Geneticin (G418; Life Technologies) and 2 μg/mL puromycin (Calbiochem, La Jolla, CA).

**Immunofluorescence and immunohistochemistry.** For immunofluorescence analysis, LNCaP cells were plated onto glass coverslips and processed as previously described (32). FLAG-tagged caCqr expression was detected using anti-FLAG antibody, M5 (Sigma, St. Louis, MO), at a 1:500 dilution and Texas Red–conjugated goat anti-mouse IgG (Jackson ImmunoResearch Laboratories, West Grove, PA) at 1 μg/mL in PBS [50 mM/L Na phosphate, 150 mM/L NaCl (pH 7.4)] containing 5% heat-inactivated goat serum. Cells were imaged using phase contrast and immunofluorescence optics (Leica, New York, NY).

For immunohistochemical analysis, tumors were excised from mice, fixed in zinc formalin, and embedded in paraffin. Tissue sections were deparaffinized in xylene and alcohol, and endogenous peroxidase activity was quenched by a 30-min incubation in 0.5% hydrogen peroxide/methanol. Tumors were deparaffinized in xylene and alcohol, and endogenous peroxidase activity was quenched by a 30-min incubation in 0.5% hydrogen peroxide/methanol. Immunofluorescence optics (Leica, New York, NY).

**Materials and Methods.**

**Cancer Research**

**Cancer Res 2007; 67: (8). April 15, 2007 3664 www.aacrjournals.org**

Cancer Research
the constitutively active, FLAG-tagged caCqr were derived (Fig. 1A). This approach was chosen because it was previously shown that transient overexpression of caCqr in LNCaP cells resulted in neuroendocrine-like differentiation (24), and that neither tetracycline nor doxycycline treatment of parental, untransfected LNCaP cells at the concentrations used had any measurable effects on LNCaP proliferation (data not shown). Figure 1B shows that treatment of a representative clone of caCqr-expressing cells (D29) with 1 μg/mL doxycycline for 3 to 6 days induced expression of FLAG-tagged caCqr in 70% to 80% of the cells, whereas Fig. 1C shows acquisition of an neuroendocrine-like morphology. Up-regulation of NSE protein levels and induction of FLAG-caCqr expression in three different clones used in subsequent studies are shown in Fig. 1D.

To determine whether caCqr-differentiated LNCaP cells also produced and secreted neuropeptides, ELISAs were done on 5-day conditioned medium from doxycycline-treated D29 cells. Results indicated that 0.167 ± 0.049 ng/mL bombesin and 0.193 ± 0.020 neurotensin were secreted into conditioned medium, whereas media from cells cultured in the absence of doxycycline had 0.064 ± 0.032 and 0.023 ± 0.005 ng/mL, respectively. As an indirect measure of the ability of caCqr-expressing cells to produce these peptides, the ability of specific antagonists of the receptors for bombesin, PTHrP, and neurotensin to inhibit proliferation of PC3 prostate cancer cells induced by conditioned medium from doxycycline-treated D29 cells was tested. Figure 2A and B shows that media from doxycycline-treated cells induced ~2-fold increase in cell number compared with the untreated control, and that antagonists of the bombesin receptor or the PTHrP receptor each partially inhibited the response. We have previously shown a similar response to the neurotensin inhibitor SR48692 (37). Moreover, when antagonists of the bombesin, PTHrP, and

Figure 1. Stable overexpression of caCqr PKA induces a neuritic phenotype in LNCaP cells. A, plasmid cDNA encoding a constitutively active mutant of PKA catalytic subunit (caCqr) was stably transfected into LNCaP cells using the Tet-On inducible system, and transfectants were subcloned as described in Materials and Methods. B, immunofluorescence microscopy of the caCqr-expressing clone D29 was done using M5 anti-FLAG monoclonal antibody following 3 and 6 d of 1 μg/mL doxycycline (doxy) treatment in T-medium + 5% FBS. C, representative phase-contrast photomicrographs of clone D29 depict cellular morphologies following treatment with vehicle or doxycycline for 5 d. D, caCqr-overexpressing stable clones (D, D29, and BB32) were cultured in T-Medium + 5% FBS and treated with vehicle or doxycycline for 3 d. Western blot analysis was done with 50 μg whole-cell lysate using anti-NSE (top), anti-FLAG (Cqr PKA, middle), and anti-ERK2 (bottom) antibodies. ERK2 represents a loading control. NT, not treated.
neurotensin receptors were combined, cell proliferation was significantly reduced even further than observed with the individual inhibitors (Fig. 2C). These findings substantiate the ELISA results and also show that neuroendocrine-like cells can exert their growth effects through the concerted action of multiple stimulatory neuropeptides. Interestingly, caCqr-induced neuroendocrine-like cells retained expression of the androgen receptor (data not shown), a finding that contrasts with the situation in human tumors (reviewed in ref. 9) and is inconsistent with the results of Wright et al. (38), who showed that knockdown of the receptor in LNCaP cells triggers neuroendocrine differentiation.

Finally, to determine whether the growth signal(s) mediated by the secreted neuropeptides required transactivation of the epidermal growth factor (EGF) receptor and its synergistic partner c-Src, (as shown in ref. 37 for neurotensin), the ability of the Src family kinase inhibitor PP2 to inhibit the growth of LNCaP cells stimulated with media from doxycycline-treated D29 cells was examined. Figure 2D shows that PP2 significantly inhibited LNCaP proliferation, almost to levels induced by media from doxcycline-un treated D29 cells. A similar result was obtained when PC3 cells were incubated with conditioned medium and PP2 (data not shown). That the EGF receptor is also required for the growth-stimulating properties of media from doxycycline-treated D29 cells was shown previously (37). Together, the results shown in Figs. 1 and 2 indicate that doxycycline-inducible overexpression of caCqr is sufficient to induce acquisition of neuroendocrine-like characteristics similar to those observed following cAMP-mediated stimulation (18, 19) and transient overexpression of caCqr (24). Therefore, the Tet-inducible caCqr expression system seemed suitable for studying neuroendocrine-like cells in vitro and possibly in vivo.

**caCqr-mediated neuroendocrine-like differentiation induces increased mitotic activity in prostate tumor cells.** Because conditioned medium from neuroendocrine-like cells only modestly stimulated prostate cancer cell proliferation (Fig. 2; ref. 37), we postulated that physical contact between neuroendocrine-like cells and tumor cells may be needed for efficient mitotic stimulation. To address this possibility, coculture experiments were done. Two thousand caCqr-positive cells and 3,000 LNCaP cells were plated together in six-well dishes, incubated with or without doxycycline in the presence of BrdUrd, and scored for the number of BrdUrd-positive cells, as a measure of mitotic activity. caCqr-expressing cells in the population were identified by anti-FLAG immunofluorescence. Figure 3A shows a representative immunofluorescent

---

**Figure 2.** Effect of neuropeptide receptor antagonists or c-Src inhibitor on proliferation of prostate cancer cells induced by neuroendocrine-like cell secretions. D29 cells were incubated in the presence or absence of 2 μg/mL doxycycline in serum-free medium for 5 d. PC3 (for neuropeptide antagonists) or LNCaP (for Src inhibitor) cells were then pretreated (or not) with inhibitor(s) for 1 h (except PP2, 15 min), incubated with D29 conditioned medium for 48 h ± inhibitor(s), and counted by hemacytometer. Columns, mean from three independent experiments; bars, SE. *, P < 0.05, relative to control; **, P < 0.05 relative to doxycycline treated (+dox). A, bombesin antagonist (BBI), 1 μmol/L; B, PTHrP antagonist (PTI), 0.16 μmol/L; C, combined BBI, PTI, and neurotensin receptor antagonist SR48692, 0.10 μmol/L; D, c-Src inhibitor PP2, 10 μmol/L.
image of a culture that contained 40% caCqr-expressing cells of clone BB32 and 60% LNCaP, in both the doxycycline-induced and uninduced conditions. Quantitation of these and four additional experiments is shown in Fig. 3B. The BB32 clone was found to induce a >2-fold increase of BrdUrd incorporation in the cocultures when caCqr expression was induced with doxycycline, compared with cells cultured in the absence of doxycycline. Analogous results were observed with cocultures containing caCqr-expressing clones D and D29 (Fig. 3B). In all three cocultures, cells that stained positively for FLAG-caCqr were distributed randomly through the microscopic fields and rarely (<0.5%) stained positively for BrdUrd incorporation. Similar results were obtained when caCqr-expressing clones were cocultured with PC3, androgen-independent cells, although basal levels of BrdUrd incorporation were higher, resulting in smaller differences between induced and uninduced cultures (data not shown). Taken together, these data indicate that LNCaP-derived neuroendocrine-like cells induce an increase in the mitotic activity of surrounding prostate tumor cells, similar in extent to that observed with conditioned medium and consistent with the paracrine hypothesis.

**Anchorage-independent growth of LNCaP cells is stimulated by caCqr neuroendocrine-like cells.** To test the possibility that caCqr neuroendocrine-like cells could affect the anchorage-independent growth of LNCaP cells, mixtures of LNCaP and caCqr-expressing cells were examined for their ability to form colonies in soft agar. In preliminary experiments, a ratio of 2.5:1.0 LNCaP/caCqr-expressing cells was found to form the greatest number of colonies in the presence of doxycycline; thus, this ratio was used in subsequent experiments. LNCaP and caCqr-expressing cells were cultured alone or in combination, at a ratio of 2.5:1, respectively, in the presence or absence of doxycycline. Figure 4 shows that no significant effect of caCqr-expressing cells on the colony-forming ability of cocultured LNCaP cells was observed in the absence of doxycycline (LN/D29 or LN/BB32), compared with that expected from the additive growth of each cell type grown independently (LN + D29 or LN + BB32). However, in the presence of doxycycline, a striking increase in soft agar colony formation in cocultures was observed. Specifically, LNCaP cells, cultured alone, were unaffected by doxycycline and produced ~700 colonies when 25,000 cells were seeded. D29 and BB32 seeded alone at 10,000 cells per plate and treated with doxycycline produced ~50 colonies, indicating that inducible neuroendocrine-like cells would contribute <0.5% of the total soft agar colonies formed in coculture. When D29 and BB32 were mixed with LNCaP cells at identical plating densities as when seeded alone and treated with doxycycline, 1,100 and 1,050 colonies were produced, respectively, yielding statistically
significant increases in both instances ($P < 0.05$), compared with the sum of LNCaP alone (700 colonies) + D29 alone ([50]) or the sum of 700 LNCaP + ~ 50 BB32 alone (~ 750), respectively. Representative examples of culture dishes for each of the variables are shown below the graph in Fig. 4. These data indicate that the presence of caCqr-expressing neuroendocrine-like cells resulted in increased soft agar colony formation by LNCaP cells that was not attributable to growth of the caCqr neuroendocrine-like cells themselves.

**Tumor growth, FLAG-Cqr expression, and PSA levels in intact male mice.** LNCaP and caCqr-expressing cells were injected alone or together into each hind flank of athymic mice at a ratio of 0.3X (caCqr cells/LNCaP), where $X = 2.5 \times 10^6$ cells. Figure 5A shows that the volume of tumors formed by LNCaP cells coinfected with caCqr cells (clone D29) was only modestly greater than and not significantly different from tumors formed by LNCaP cells alone. In addition, neither the frequency nor the rate of tumor formation was appreciably altered by the presence of caCqr cells. Similar results were observed when mice were coinfected with caCqr and LNCaP cells at a ratio of $X:X$ (data not shown). Infection of D29 cells alone induced few tumors (3 of 15 compared with 100% for the other two groups of mice) of very small size (<20 mm$^3$) compared with 400 mm$^3$ of coinjected animals), consistent with the previously observed decrease in mitotic activity of these cells in the presence of doxycycline.

To verify that animals injected with FLAG-caCqr cells still expressed this protein during tumor formation, tumors removed at the termination of the experiment were analyzed by Western immunoblotting. Figure 5B (lane 6) shows FLAG-Cqr expression in tumors from animals coinjected with 0.3X caCqr cells/LNCaP and treated with doxycycline, but not in tumors from LNCaP or caCqr cells alone that underwent doxycycline treatment, or from any doxycycline-untreated animals. Densitometric analysis revealed a ~ 3-fold increase in FLAG antibody reactivity in lane 6 versus lane 2, when levels of FLAG-caCqr were normalized to the MAPK loading control. Immunohistochemical analysis substantiated the presence of FLAG-positive cells in tumors of coinjected mice, which were absent in tumors derived from LNCaP cells alone (Fig. 5C). The frequency of FLAG-positive cells ranged from 0% to 15%, with most samples showing 2% to 3% positivity and the highest levels in tumors of the 0.3X mice.

Because tumor volumes of the 0.3XX group were insignificantly but consistently greater than those of the 0.X group, serum PSA values were measured in repeat experiments to determine whether PSA levels might reflect some metabolic differences between the two groups. Figure 5D shows that significantly higher levels of PSA were found in the 0.3XX D29/LNCaP group compared with the 0.X D29/LNCaP group at 12 and 13 weeks after tumor cell inoculation, whereas, again, no significant differences in tumor take, rate, or size were noted. Under androgenic conditions, caCqr-expressing cells treated with doxycycline produced similar amounts of PSA as did the parental LNCaP cells (data not shown). However, because caCqr neuroendocrine-like cells are mitotically inactive, and because only 0.3X was used, the contribution of PSA produced by caCqr cells was considered negligible. These data suggest that the increased PSA release, while correlating with enhanced growth, is more likely attributed to increased PSA production than to increased proliferation, and that PSA levels may be a more sensitive
indicator of effects of neuroendocrine-like cells on the LNCaP tumor cells than in tumor growth in androgen-replete conditions.

cacq neuroendocrine-like cells enhance tumor growth in castrated mice. To reproduce in animals, the androgen-independent conditions used in in vitro growth assays, animals bearing tumors were castrated and then monitored for changes in tumor growth. Figure 6A and B shows that in two independent experiments, within a few weeks following castration, tumor growth rates were significantly increased when cacq cells were present, compared with rates of tumors containing only LNCaP cells. In the absence of doxycycline treatment, no significant rate differences were observed between the tumors containing or lacking cacq cells (data not shown). In a third independent experiment under the same conditions, the mean tumor volume tripling times were calculated to be 7.9 ± 0.7, 5.8 ± 0.4, and 4.0 ± 0.6 weeks for D29/LNCaP ratios of 0:X, 0.3:X, and X:X, respectively. These results indicate that cacq neuroendocrine-like cell effects on tumor size may be most significant under reduced androgen conditions and are consistent with the notion that neuroendocrine-like cells in human prostate cancers contribute to androgen-independent disease.

Immunohistochemical analysis of tissue sections prepared from tumors removed at the end of these experiments was done, but the quality of the images was poor due to the highly necrotic and neovascularized nature of the tumors. Therefore, although no FLAG-positive cells were observed in any of the tumors examined, interpretation was compromised, and no definitive conclusion was drawn regarding their abundance.

Discussion

Human prostatic adenocarcinomas frequently contain neuroendocrine-like cells that increase in number with disease progression, and multiple reports suggest that neuroendocrine-like cells are involved in acquisition of the androgen-insensitive state, a characteristic of late-stage cancers (39). Mechanistically, it has long been postulated that neuroendocrine-like cells secrete factors capable of enhancing the survival or replication of surrounding
neuroendocrine-like model seem to more closely resemble those of neuroendocrine-like cells in human prostate cancers than do those of the NE-10 model. For example, it is not clear whether the constellation of factors secreted by the NE-10 cells are similar to or distinct from those secreted by neuroendocrine-like cells in human tumors because characterization of such molecules has not been reported for NE-10 cells. To date, factors produced and secreted by caPKA-induced neuroendocrine-like cells are identical to those produced by neuroendocrine-like cells in human prostate tumors and include the neuropeptides, bombesins, PTHrP, neurotensin, serotonin, etc. (Fig. 2; accompanying text; data not shown; ref. 6).

The mitotic nature of the neuroendocrine-like cells in the two models can also be compared. The caPKA-induced neuroendocrine-like cells are poorly mitotic or nonmitotic (similar to those in human prostatic cancers), whereas NE-10 cells are highly proliferative and representative of pure neuroendocrine tumors derived from other tissues, such as lung. As such, if mixed with prostate tumor cells, NE-10 cells would likely assume a significant volume of the resulting tumor. We believe this not to be the case with the caPKA-induced neuroendocrine-like cells. Although one third or equal numbers of caPKA-induced neuroendocrine-like cells were initially cocultured or coinjected with LNCaP tumor cells (Figs. 3–6), the PKA-expressing cells ceased dividing in the presence of doxycycline and contributed insignificantly to the number of proliferative cells in coculture studies (<0.5% of total; Fig. 3) or to the volume of tumors formed in coinjected animals (range, 0–15% between tumors and between multiple slices of the same tumor; Fig. 5).

In spite of the fact that the majority of coinjected tumors contained few or no neuroendocrine-like cells, the presence of 15% FLAG–PKA–positive cells in one of the coinjected xenografts suggests that the cells might not be entirely post-mitotic. One reason for this apparently high percentage (given the premise that the neuroendocrine-like cells should be greatly overgrown by the tumor cells) could be uneven exposure of the caPKA-expressing cells to doxycycline or to variable responses of the engineered cells to doxycycline during the long-term experiment. Nevertheless, the frequency and size of the tumors formed by caCqr cells alone in the presence of doxycycline were very small (<20 versus 400 mm³ in intact animals and 4,000 mm³ in castrated animals). These data together with the finding that in intact (noncastrated) animals coinjected with caCqr and LNCaP cells, no significant differences in tumor volume between coinjected and singly injected animals were seen (Fig. 5A, ■ and ◆, respectively) suggest that caCqr cells did not contribute significantly to the tumor mass that formed in coinjected, castrated animals (Fig. 6A and B).

The variation in abundance of neuroendocrine-like cells detected in the PKA-induced neuroendocrine-like cell model is also similar to that of neuroendocrine-like cells found in late-stage human tumors (reviewed in refs. 6, 9, 41). The bulk of the evidence indicates a low occurrence of neuroendocrine-like cells in human primary tumors that increases with androgen-independent growth and cancer progression. However, Roudier et al. found wide variation in neuroendocrine positivity in separate metastases within and among 14 patients who died of prostate cancer metastasis to the bone (41). Although, in most patients <1% of tumor cells in all metastatic sites expressed CgA, in four patients, 6.5% to 100% of tumor cells expressed CgA in some, but not all sites. Thus, the range of abundance of neuroendocrine-like cells found in the caCqr-NE cell model is well within the range found in human tumors. In summary, whereas the two mouse models for

### Figure 6

**caCqr neuroendocrine-like cells enhance androgen-independent growth of LNCaP tumors in nude mice.** caCqr-expressing cells of clone D29 were injected s.c. with or without LNCaP cells in the indicated ratios, where \( X = 2.5 \times 10^{10} \) cells. Animals were administered doxycycline in their drinking water, as described in Fig. 5 legend. Animals that possessed tumors of \( \sim 100 \text{ mm}^3 \) in volume that had shown growth for two consecutive weeks were castrated (9 wks following tumor cell injection and 5 wks following the onset of tumor growth), and monitoring of tumor growth continued. Points, mean tumor volume calculated from the number of tumors indicated; bars, SE. Two representative experiments. Statistical significance was determined by Student’s t test. A, ◆, 0:X D29/LNCaP (\( N = 8 \)); ■, 0.3:0:X D29/LNCaP (\( N = 4 \)). *, \( P < 0.05 \) relative to 0:X. B, ◆, 0:X D29/LNCaP (\( N = 9 \)); ■, X:X D29/LNCaP (\( N = 4 \)). *, \( P < 0.05 \), relative with 0:X.

---

tumor cells, but direct causal analysis of neuroendocrine-like cell effects within prostate tumors has been lacking. This study provides that causal evidence, which supports the paracrine hypothesis of neuroendocrine-like cell function in prostate cancer progression.

The paracrine activity of neuroendocrine-like cells and their effects on LNCaP cells have been shown in another mouse model of prostate cancer in which a mouse prostate neuroendocrine tumor (NE-10), derived from the LPB-Tag 12T-10 “Tramp” transgenic mouse, enhanced the growth of LNCaP xenografts in castrated, athymic mice, when injected contralaterally to the LNCaP cells (40). Although the overall results of the NE-10 cell study are similar to those reported here, some characteristics of the caPKA-induced
PKA-Mediated Neuroendocrine Differentiation

Received 7/17/2006; revised 12/12/2006; accepted 2/2/2007.

Grant support: Department of Health and Human Services National Cancer Institute grants ROI 76669 and PO1 CA76465 (S.J. Parsons) and National Cancer Institute of Canada grant 012003 (M.E. Cox).

Acknowledgments

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

We thank Dr. L.W. Chung for providing LNCaP cell lines and advice on their maintenance. Dr. G.S. McKnight for the caPKA subunit cDNA used to generate the stable Cgr cell lines. Sandia-Aventis for generously providing the neurotensin receptor antagonist SR48692, and Drs. M.J. Weber, J.T Parsons, D. Gioeli, J. Dasilva, and D. Theodorescu for their conceptual and technical insights.

Our use of caPKA to induce neuroendocrine-like differentiation raises the question of whether all neuroendocrine-like cells in human tumors arise from elevated intracellular levels of cAMP and subsequent activation of PKA. This question has not been addressed systematically in human tumors, but anecdotal evidence suggests that it may be one relevant mechanism of neuroendocrine cell induction. First, androgen deprivation of LNCaP cells in culture results in a 9-fold elevation in levels of intracellular cAMP suggesting that PKA may be activated in these cells under these conditions (27). The cytokine interleukin-6 can also induce a small but significant activation of PKA in cultured LNCaP (24).

Additional evidence that PKA may be activated in human prostate cancers comes from the studies of Kvissel et al. (42), who observed that the Cj2 splice variant of the catalytic subunit of PKA is up-regulated in human prostate tumor cells compared with normal prostatic tissue. Although activation of PKA may be one mechanism by which neuroendocrine cells arise, other PKA-independent mechanisms of differentiation are clearly possible, resulting in neuroendocrine-like cells with different molecular characteristics, as described by Zelivianski et al. (43) and, perhaps, with different functions.

The elucidation of PKA as a key mediator of neuroendocrine-like differentiation both in vitro and in vivo raises the possibility of therapeutically targeting activated PKA and induction of neuroendocrine-like differentiation in prostate cancer patients. By using the mouse model described in this report, pharmacologic inhibitors of PKA or antagonists of the neuropeptides secreted by neuroendocrine-like cells can be tested for their ability to inhibit tumor growth, survival, and/or metastasis, thus reducing the number or effectiveness of neuroendocrine-like cells. Targeting the signaling pathways of tumor cells responding to neuroendocrine cell-derived factors provides an alternative approach.

References


Androgen-Independent Growth and Tumorigenesis of Prostate Cancer Cells Are Enhanced by the Presence of PKA-Differentiated Neuroendocrine Cells

Paul D. Deeble, Michael E. Cox, Henry F. Frierson, Jr., et al.


Updated version  Access the most recent version of this article at:
http://cancerres.aacrjournals.org/content/67/8/3663

Cited articles  This article cites 43 articles, 9 of which you can access for free at:
http://cancerres.aacrjournals.org/content/67/8/3663.full.html#ref-list-1

Citing articles  This article has been cited by 8 HighWire-hosted articles. Access the articles at:
/content/67/8/3663.full.html#related-urls

E-mail alerts  Sign up to receive free email-alerts related to this article or journal.

Reprints and Subscriptions  To order reprints of this article or to subscribe to the journal, contact the AACR Publications Department at pubs@aacr.org.

Permissions  To request permission to re-use all or part of this article, contact the AACR Publications Department at permissions@aacr.org.