Retinol Metabolism and Lecithin:Retinol Acyltransferase Levels Are Reduced in Cultured Human Prostate Cancer Cells and Tissue Specimens

Xiaojia Guo, Beatrice S. Knudsen, Donna M. Peehl, Alberto Ruiz, Dean Bok, Robert R. Rando, Johnh S. Rhim, David M. Nanus, and Lorraine J. Gudas

INTRODUCTION

Vitamin A and its natural and synthetic analogues, a group of compounds known as retinoids, have many chemopreventive and chemotherapeutic actions in various experimental models for human cancer (reviewed in Refs. 1–3). In addition, retinoids are currently being used for the treatment of acute promyelocytic leukemia and for the treatment of patients with prostate cancer (see examples in Refs. 21 and 22). In a variety of studies using cultured human prostatic cancer cells, retinoids have been shown to inhibit tumor cell growth. For instance, the growth of the androgen-sensitive LNCaP cell line (23–29) and androgen-independent prostatic cancer cell lines (30–32), as well as primary cultures from prostatic adenocarcinomas (33, 34), can be inhibited by retinoids. Retinoids can also inhibit the ability of these tumor cells to invade the extracellular matrix (35–37). The mechanisms by which RA can induce growth inhibition of prostate cancer cell lines are unclear, but studies have implicated apoptosis (23, 38, 39), activation of retinoblastoma protein (29), and modulation of androgen receptor pathways (27, 39). It has also been shown recently that the Bcl-2 protein is down-regulated by RA in prostatic cancer cells (40).

Normal human prostatic epithelial cells, similar to cancer cells, are also growth inhibited by RA (33). Immortalization of these cells with SV40 T antigen did not appreciably alter responsiveness to RA (41). However, introduction of the ras oncogene into these immortal cells then created a tumorigenic cell line that became less responsive to RA-associated growth inhibition (42). The involvement of the retinoid receptors in the growth-inhibitory response has been suggested by numerous studies, such as the demonstration that the expression of RARβ could sensitize prostatic cancer cells to growth inhibition mediated by combinations of retinoids and a vitamin D analogue (25). The importance of RARβ with respect to the sensitivity of cells to}
RA-induced growth inhibition was further indicated by a very recent study, performed on human radical prostatectomy tissue specimens, which showed that RARβ and RXRβ mRNAs were selectively lost in both prostate cancer and adjacent, morphologically normal prostatic tissue (43). In addition to the abnormally low levels of RARβ and RXRβ in prostate cancers, it was shown that in benign prostatic hyperplasia the concentration of retinol was 2-fold elevated, but in prostate carcinoma the level of RA was five to eight times lower than in normal prostate or in benign prostatic hyperplasia (44). These findings suggest that there are abnormalities in the expression of the enzymes that metabolize retinoids in human prostate cancers.

The pathways for the metabolism of retinol and RA in various types of cells are complicated and are only beginning to be elucidated at a molecular level (reviewed in Refs. 45 and 46). The cDNA encoding one of the enzymes involved in retinol metabolism, LRAT, was cloned recently (47). We have shown that cultured human carcinoma cells, including those from the head and neck, breast, skin, and kidney, do not esterify retinol to the same extent as normal cultured epithelial cells from these same tissues. These data suggest that the inappropriate cell growth and the loss of normal differentiation responses in these tumor cells may in part result from the lack of a sufficient amount of internal retinol stored as retinyl esters (48–51). In this study, we examined the metabolism of retinol and RA in cultured normal and malignant human prostatic epithelial cells. We show that the cancer cells are not able to metabolize significant amounts of retinol to retinyl esters, and that this lack of retinol esterification is correlated with the absence of LRAT protein expression. We also show that LRAT protein is not expressed in prostatic carcinoma cells in tissue specimens from human patients.

MATERIALS AND METHODS

Materials. Radiolabeled retinol (all-trans [11,12-3H]; specific activity, 27–47 Ci/nmol) was purchased from New England Nuclear/Dupont (Boston, MA). All other chemicals used, unless specified, were purchased from Sigma Chemical Co.-Aldrich (St. Louis, MO).

Cells and Culture Conditions. The origins and properties of the cell strains and lines used have been described previously (Table 1). One normal human prostate epithelial cell strain (PrEC) was obtained from Clonetics Corp. (Walkersville, MD) and was cultured according to the manufacturer’s instructions. The other normal cell strain (E-PZ-10) was derived in the laboratory of Dr. Peehl from histologically normal tissue of the peripheral zone of a radical prostatectomy specimen (52). Culture methods were as described previously (52). Epithelial cell strains were also derived from adenocarcinomas of the prostate of Gleason grade 3/3 (E-CA-11), 3/4 (E-CA-21), 4/3 (E-CA-91), and 4/4 (E-CA-37). The RPrNS-1-1 line and pRNS-1-1/ras cell lines were derived and cultured as described previously (42). The LNCaP, DU 145, Tsu-Pr1, PPC-1, PJ-1, and PC-3 cells were maintained in a consensus medium consisting of a mixture of DMEM and Ham’s F-12 medium (1:1) supplemented with 5% FCS, 0.4 µg/ml hydrocortisone, 10 µg/ml epidermal growth factor, and 5 µg/ml insulin (53). Normal human mammary epithelial cells were from Clonetics and were cultured as described previously (50). For radiolabeling studies, Northern and Western analyses of all of the cell strains and lines and a consensus medium consisting of DMEM plus 5% fetal bovine serum were used.

[3H]Retinol Radiolabeling, Extraction of Retinoids, and HPLC. Radio- labeling and retinoid extractions were as described previously (49). Nonradioabeled retinoid standards were added to the samples before extraction. Briefly, 350 µl of acetonitrile:butanol (50:50, v/v) and 0.1% butylated hydroxytoluene were added to 0.5 ml of cells or medium samples. The mixtures were vortexed thoroughly for 30 s. After addition of 300 µl of a saturated (1.3 kg/l) K2HPO4 solution and thorough mixing, the samples were centrifuged for 10 min at 3000 × g. The upper organic layer was collected and transferred to an injector vial for automated HPLC analysis.

The HPLC analysis was performed using a Waters Millennium system (Waters Corp., Milford, MA) to separate the various retinoids. Samples were applied to an analytical 5-µm reverse-phase C18 column (Vydac, Hesperia, CA) at a flow rate of 1.5 ml/min, as described (48–51).

Retinoids were identified by HPLC based on at least two criteria: an exact match of the retention times of unknown peaks with those of authentic retinoid standards and identical UV spectra (220–400 nm) of unknowns against spectra from authentic retinoid standards during HPLC by using the photo detector array detector. RA was also identified by the shift of the retention time of the methylated RA derivative (48).

Western Analysis. This procedure was carried out as described previously (47, 50, 51). Briefly, polyclonal antiserum were generated to a mixture of two different LRAT peptides in rabbits. Total cell protein was used, and Western blot analysis on nitrocellulose filters was performed using antisera diluted to 1:1000 for detection of LRAT. Protein bands were detected by the ECL system (Pierce, Rockford, IL).

Immunohistochemistry. Paraffin-embedded tissues were obtained from prostate cancer patients with Institutional Review Board approval. Antigen retrieval was performed in citrate buffer (pH 6.0) in a pressure cooker for 10 min. Affinity-purified LRAT antibody was used at a 1:500 dilution. As a control, the antibody was preincubated with the peptide. Sections were stained using the TechMat 500 machine as specified by the manufacturer (Verhave, Inc.). Secondary antibodies were horse-radish peroxidase conjugated (1:1000 dilution), and diaminobenzidine was used as a substrate. Several specimens from six different patients were examined. Slides were analyzed by a pathologist (B. S. K.).

RESULTS

Metabolism of [3H]Retinol in Cultured Normal and Malignant Human Prostatic Epithelial Cells. We first examined [3H]retinol metabolism in cultured normal and malignant human prostatic epithelial cells to determine whether differences in retinol metabolism were present. Cells were cultured in the presence of 50 nM [3H]retinol for various times (22 h is shown in Fig. 1). Cells and medium were then harvested, retinoids were extracted, and the metabolites of [3H]retinol were analyzed by HPLC. Nonradiolabeled retinoid standards were added to each sample to allow the identification of many of the radiolabeled retinoids. The HPLC tracings of [3H]retinol and its metabolites from two normal human prostatic epithelial cell strains, PrEC and E-PZ-10, and from six prostate cancer cell lines are shown (Fig. 1). The normal cell strains esterified almost all of 50 nM [3H]retinol, whereas the ability to esterify [3H]retinol was greatly impaired in all prostate cancer lines (Fig. 1). [3H]RA was synthesized from [3H]retinol by the PC-3 prostate cancer line, whereas only trace amounts of [3H]RA were produced by the LNCaP, DU 145, and Tsu-Pr1 tumor lines. The normal epithelial cell lines did not synthesize detectable amounts of [3H]RA from [3H]retinol (Fig. 1).
The calculation of the total amount of $[^3]$Hretinol remaining over time is an indicator of the amount of retinol metabolized into all types of metabolites; all of the $[^3]$Hretinol remaining, including both the $[^3]$Hretinol still in the medium and the intracellular $[^3]$Hretinol, was measured. The time course of $[^3]$Hretinol metabolism is shown in Fig. 2. The normal prostatic epithelial cell strain PrEC metabolized $\sim$75% of the 50 nm $[^3]$Hretinol within 4 h, whereas the two prostate carcinoma lines, LNCaP and PC-3, metabolized $<$5% of the $[^3]$Hretinol in the 24-h time period. Two additional cell lines were tested in this assay, pRNS-1-1 and pRNS-1-1/ras. pRNS-1-1 is a line of normal human prostatic epithelial cells immortalized with SV40, and the tumorigenic pRNS-1-1/ras line was created by stable transfection with activated ras. These two cell lines metabolized a modest amount of $[^3]$Hretinol over the 24-h time period, approximately 20–25% of the total $[^3]$Hretinol (Fig. 2). These data suggest that the introduction of an oncogene such as the SV40 T antigen into normal human prostatic epithelial cells can lead to a reduction in the ability of the cells to metabolize $[^3]$Hretinol.

It is apparent from the tracings in Fig. 1 that much of the $[^3]$Hretinol was esterified by the normal prostatic cells. The intracellular concentrations of the $[^3]$Hretinyl esters synthesized from $[^3]$Hretinol are shown in Fig. 3. Only the normal cell strains exhibited high intracellular levels of these $[^3]$Hretinyl esters. The two cancer lines LNCaP and PC-3 exhibited almost no intracellular $[^3]$Hretinyl esters (Fig. 3A). The levels of $[^3]$Hretinyl esters in the pRNS-1-1 and pRNS-1-1/ras lines were also much lower than those in the normal epithelial cell strains (Fig. 3A). Primary epithelial cell strains isolated from adenocarcinomas of Gleason grades 3 and/or 4 (see Table 1) were analyzed similarly. All of these cancer cell strains also exhibited lower levels of $[^3]$Hretinyl esters as compared with the levels in the normal cell strains (Fig. 3A).

Related data from other prostatic cancer cell lines are shown in Fig. 3B. None of the six tumor cell lines tested exhibited significant esterification of $[^3]$Hretinol to the $[^3]$Hretinyl esters. The time course of the formation of the intracellular $[^3]$Hretinyl esters is shown in Fig. 3C. It can be seen that formation of the intracellular $[^3]$Hretinyl esters in the normal prostatic epithelial cells was rapid, with the majority of the retinyl esters synthesized from retinol in the first 4 h after the addition of 50 nm $[^3]$Hretinol to the medium. In contrast, the pRNS-1-1, pRNS-1-1/ras, LNCaP, and PC-3 tumor cell lines exhibited much less synthesis of $[^3]$Hretinyl esters even at 22 h after $[^3]$Hretinol addition (Fig. 3C). These results from the prostate cancer cells (Figs. 1–3) are similar to those that we reported previously for human carcinoma cells from the oral cavity, breast, and kidney (48–51). It was shown previously that pretreatment with RA could increase retinol esterification in some cell types. To ascertain whether this would also be true in prostate cells, normal and malignant cells were cultured in 1 $\mu$M RA for 48 h. The medium was then changed, and $[^3]$Hretinol was added to the medium. Culture of the cells for 48 h in the presence of 1 $\mu$M RA before the treatment with $[^3]$Hretinol increased the levels of intracellular retinyl esters in all of the cells except for LNCaP and PC-3 by approximately 15–30% (Fig. 3A).

Analysis of LRAT Protein Expression. Because of the large reduction in $[^3]$Hretinol esterification observed in the prostatic carcinoma cells as compared with the normal prostatic epithelial cells, we examined the expression of the LRAT protein, which is responsible for retinol esterification in many cell types, by Western analysis using a polyclonal antibody against human LRAT (47). LRAT protein with a molecular mass of approximately 62–65 kDa was observed in the normal epithelial cell strains (Fig. 3A). It can be seen that formation of the intracellular $[^3]$Hretinyl esters in the normal prostatic epithelial cells was rapid, with the majority of the retinyl esters synthesized from retinol in the first 4 h after the addition of 50 nm $[^3]$Hretinol to the medium. In contrast, the pRNS-1-1, pRNS-1-1/ras, LNCaP, and PC-3 tumor cell lines exhibited much less synthesis of $[^3]$Hretinyl esters even at 22 h after $[^3]$Hretinol addition (Fig. 3C). These results from the prostate cancer cells (Figs. 1–3) are similar to those that we reported previously for human carcinoma cells from the oral cavity, breast, and kidney (48–51).
PrEC protein extract but not in extracts from the prostate cancer lines (Fig. 4A). In addition, the level of LRAT protein was greatly reduced in the pRNS-1-1 and pRNS-1-1/ras lines relative to the normal PrEC cells (Fig. 4B). These protein data are consistent with the data shown in Fig. 1 indicating that the PrEC cells esterify much more retinol than the prostate cancer cells. These data strongly suggest that LRAT protein is expressed at much lower levels in the carcinoma cells as compared with the normal prostate epithelial cells.

The Metabolism of [3H]RA in Normal versus Malignant Prostate Epithelial Cells. In this series of experiments, normal and cancer cells were treated with 50 nM [3H]RA for various times, followed by cell harvest and retinoid extraction. The metabolites of [3H]RA were then examined by HPLC (Fig. 5). A low rate of [3H]RA metabolism was observed in the majority of the cancer cell lines, although the DU 145 and PJ-1 cancer lines metabolized almost all of the [3H]RA over a 20-h culture period (Fig. 5). Quantitation of [3H]RA metabolism in these various lines indicated that ~95% of the 50 nM [3H]RA was metabolized in 20 h by the DU 145 and PJ-1 cell lines, whereas the LNCaP and PC-3 cell lines metabolized almost none of the [3H]RA during this time period (data not shown). The normal cell strains metabolized only a moderate amount of [3H]RA (data not shown).

The ability to metabolize [3H]RA to more polar metabolites in the DU 145 line correlated with the expression of CYP26 (RA hydroxylase) transcripts (data not shown). The cytochrome P-450 enzyme CYP26 uses RA as a substrate (54–59). Only the DU 145 cells expressed significant levels of CYP26 mRNA, and this was seen only after the cells were cultured in the presence of 1 μM RA for 48 h. Although the normal cells and PJ-1 cells metabolized some [3H]RA, these cells did not express CYP26 mRNA (data not shown), suggesting that other enzymes may carry out RA metabolism in these cells.

Cell Growth Inhibition by Retinoids. We compared the growth inhibition by RA and 4-oxoretinoic acid in the prostate cancer cell lines DU 145, PC-3, and LNCaP to ascertain whether growth inhibi-
tion correlated with the reduced ability to metabolize RA, because this would result in higher internal RA levels. If this were the case, the DU 145 line would be less growth inhibited by RA than the PC-3 and LNCaP tumor lines. However, no correlation was found. All three of the cell lines were not growth inhibited by either RA or 4-oxoretinoic acid (Fig. 6). Thus, although a correlation between RA metabolism and RA growth inhibition has been observed in some tumor lines (60–62), there was no correlation between the ability of the cells to metabolize RA and the inhibition of the growth of these cells by all-trans RA and 4-oxoretinoic acid.

**LRAT Expression in Human Prostate Tumor Specimens.** Prostate cancer tissue specimens and benign human prostatic tissues were procured from the Pathology Department, Weill Medical College of Cornell University. The expression of LRAT was analyzed in benign prostate epithelium and in prostate cancer by immunohistochemical staining of five separate radical prostatectomy specimens. In all cases, LRAT was highly expressed in basal prostate epithelial cells, whereas secretory cells stained to a lesser extent (Fig. 7A). Stromal cells were also negative. The preimmune serum from the same rabbit did not react with basal cells (Fig. 7B). In the six prostate cancer cases with Gleason grades 3 or 4, the tumor cells did not express LRAT (one sample; Fig. 7A, arrows). Thus, these in vivo findings corroborate the results from cell culture studies. The primary prostate epithelial cell cultures consist of basal and intermediate/transiently proliferating cells and show high LRAT expression (Fig. 4). In contrast, primary cultures derived from tumor tissue, ras-transformed primary cells, and prostate cancer cell lines are negative for LRAT expression. Taken together, these data strongly suggest that prostate cancer cells do not express LRAT and that the culture system can be used for further studies of the regulation of LRAT expression.

**DISCUSSION**

We have demonstrated that human prostatic carcinoma cells exhibit a greatly reduced ability to metabolize [3H]retinol to [3H]retinyl esters...
relative to normal prostatic epithelial cells (Fig. 1). These data extend our previous research, which has shown that the ability to metabolize [3H]retinol to [3H]retinyl esters is greatly decreased in carcinoma cells from the breast (48), the oral cavity and skin (49, 50), and the kidney (51). LRAT is the enzyme responsible for this metabolism (Fig. 8). We also demonstrate that prostatic cancer cells express little or no LRAT protein as compared with normal prostatic epithelial cells (Figs. 4 and 7). We do not yet know the mechanism by which the expression of the LRAT protein is altered in cancer cells versus normal epithelial cells. However, our results to date strongly suggest that a major alteration in LRAT transcripts and the lack of expression of LRAT protein are common features of cultured human carcinoma cells (48–51). In skin, the other tissue system in which we have examined LRAT expression by immunocytochemistry, LRAT is expressed essentially in a gradient, with most dense expression in the basal layer and least dense expression in the most superficial, upper layer of the skin (49, 50).

It is interesting to note that expression of the gene $\alpha(\text{OH})_2$ase is also significantly decreased in both primary cultures of prostatic cancer cells and prostate cancer cell lines compared with normal prostatic epithelial cells (63). The enzyme $\alpha(\text{OH})_2$ase converts 25-hydroxyvitamin D$_3$ to the active metabolite 1a,25-dihydroxyvitamin D$_3$. Extensive studies have demonstrated antiproliferative and prodifferentiation activity of 1a,25-dihydroxyvitamin D$_3$ on prostatic epithelial cells (64). Loss of activity of two enzymes, LRAT and $\alpha(\text{OH})_2$ase, relevant to the synthesis of two potent antiproliferative and prodifferentiation factors would be biologically significant in the development of prostatic cancer.

Tumor progression occurs in most types of cancers, including prostate cancer (65–68). The increasing tumorigenicity of the cells is associated with increased numbers of mutations and chromosomal instability (reviewed in Refs. 65–68). Analyses using established cancer cell lines are not useful for determining whether the loss of LRAT protein expression is an early or late event in tumor progression, because all of the tumor lines were established from late-stage cancers. However, the results from our analyses of primary cultures derived from cancers of Gleason grade 3 (well-differentiated) and grade 4 (less differentiated) suggest that loss of LRAT may be an early event because even the cell strain from grade 3/3 cancer did not express LRAT. The pattern of expression of LRAT in the pRNS-1-1 cell line versus the pRNS-1-1/ras cell line also supports the possibility that the loss of LRAT protein expression is an early event in the tumorigenesis pathway. As shown in Fig. 4B, the pRNS-1-1 line, immortalized with the SV40 T antigen, exhibited a low level of expression of the LRAT protein, whereas the tumorigenic pRNS-1-1/ras line did not exhibit detectable LRAT expression. Consistent with this, these two cell lines exhibited much lower levels of retinol esterification than those observed in normal prostatic epithelial cell strains (Fig. 3A). Intriguingly, the pRNS-1-1/ras cells were unresponsive to the growth-inhibitory signals of RA, whereas the pRNS-1-1 cells were sensitive to RA growth inhibition (42).

Normal human prostate epithelia consist of two cell layers, the basal layer and the luminal or secretory layer. The basal cells have proliferative potential and are classically identified by markers such as keratins 5 and 14. Differentiated secretory cells express keratins 8 and 18, prostate-specific antigen, and androgen receptors (69). Malignant prostatic epithelium does not contain basal cells. Given that LRAT expression was observed primarily in the basal cells of the normal prostate epithelium in our immunohistochemical studies, the lack of expression of LRAT in cancer may result from the absence of basal cells in cancer. However, the cell culture data suggest that this explanation is too simplistic. The cultured normal prostatic epithelial cells correspond to the basal cells and/or “transiently proliferating/amplifying” cell population that has both a shorter life span and the ability to proliferate (69, 70). Primary cultures of both normal and cancer-derived cells express markers of basal as well as secretory cells, with no apparent differences between the normal and malignant cells (52, 71). Therefore, the differential expression of LRAT between the primary normal and cancer-derived cultures cannot be correlated with a basal versus a secretory phenotype. Although “normal” cells immortalized by SV40 maintain some LRAT expression, upon transformation by the ras oncogene, LRAT protein expression is lost. Assuming that introduction of oncogenic ras does not cause differentiation but increases oncogenicity, the results are consistent with the loss of LRAT protein as a result of malignant transformation. The decrease in LRAT expression in epithelial cells derived from prostate cancer tissue compared with cells obtained from areas of nonmalignant prostate supports the argument that LRAT is down-regulated as a result of oncogenic transformation.

There is a large amount of data for the prostate and other types of epithelia that retinoids are required for normal differentiation (33, 72–74). Expression of the LRAT enzyme would allow basal cells to accumulate and store large amounts of retinyl esters, later using hydrolase enzymes to convert the retinyl esters to more active retinoids such as RA upon differentiation into luminal cells. When the
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LRAT protein is not expressed, as in prostate cancer cells (Figs. 4 and 7), retinyl ester stores cannot accumulate, and as a result, the normal differentiation program may not transpire. An important next step will be to determine how the introduction of the SV40 T antigen and/or the differentiation program may not transpire. An important next step will be to determine how the introduction of the SV40 T antigen and/or the differentiation program may not transpire. An important next step will be to determine how the introduction of the SV40 T antigen and/or the differentiation program may not transpire. An important next step will be to determine how the introduction of the SV40 T antigen and/or the differentiation program may not transpire. An important next step will be to determine how the introduction of the SV40 T antigen and/or the differentiation program may not transpire.

We have shown that most of the prostatic carcinoma lines do not metabolize [1^H]RA very rapidly (Fig. 5). Rapid metabolism of RA to polar RA metabolites has been shown to be correlated in some cell types with sensitivity to growth inhibition by RA (60–62). These prostate cancer data are not consistent with these earlier data from other types of carcinoma lines in that the DU 145 and the PJ-1 cell lines metabolize [1^H]RA rapidly (Fig. 5), but neither cell line was growth arrested by RA (DU 145, Fig. 6; PJ-1, data not shown). Additionally, no detectable metabolism of [1^H]retinoic to [1^H]RA was observed in normal prostate epithelial cells or in the prostate tumor lines, with the exception of the PC-3 line (Fig. 1). The PC-3 line was not growth inhibited by exogenously added RA (Fig. 6). Thus, there does not appear to be a correlation between the ability of cells to metabolize retinol to RA and their ability to be growth inhibited by pharmacological doses of RA (Figs. 1 and 6).

In summary, our data in cell lines and in tissue specimens show a major reduction in LRAT expression upon neoplastic transformation of prostate epithelial cells. This suggests that restoration of LRAT metabolism may be a reasonable strategy for PC prevention and/or therapy. Future studies will further define the role of retinoid metabolism in the development and progression of prostate cancer.

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REFERENCES


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