Evaluation of Lipophilins as Determinants of Tumor Cell Response to Estramustine


Departments of Cell and Molecular Pharmacology and Experimental Therapeutics (J.M.T., V.B., K.D.T.) and Pharmaceutical Sciences (D.M.T.), Medical University of South Carolina, Charleston, South Carolina; and Department of Biological Sciences, University of Illinois, Chicago, Illinois (Z.L.)

Received June 10, 2005; accepted August 23, 2005

ABSTRACT

Estramustine administered orally as estramustine phosphate (EMP) remains a major tool in hormone refractory prostate cancer chemotherapy. The presence of estramustine binding protein, prostatin, in prostate tissue may be a determinant of response to treatment. Lipophilins are secretory proteins with homology to prostatin. Reverse transcription-polymerase chain reaction was performed to estimate expression patterns of lipophilins A to C in human biopsies and cell lines resistant to estramustine. Although lipophilin A was not expressed in prostate tissue, both lipophilins B and C were expressed in normal and tumor prostate without significant differences. For lipophilin C, a somatic mutation (T to C transition at positions 409 and 412) was found in human tumor samples and absent in normal prostate tissue. No consistent response to EMP was observed in enhanced green fluorescent protein (EGFP)-tagged lipophilin C-transfected PC3 cells compared with parental controls. Among these EGFP-lipophilin C clones, no direct correlation between response to EMP treatment (IC50 values) and EGFP expression was observed ($p = 0.73$). Lipophilin C mRNA levels did not vary significantly between wild-type and estramustine-resistant cells in prostate (DU145 and PC3) and ovarian (SKOV3) cancer cell lines. Overall, these results suggest that lipophilins are not specific determinants of estramustine efficacy.

Estramustine phosphate [estradiol 3-(bis 2-chloroethyl carbamate) 17-dihydrogen phosphate], a clinically administered anticancer drug, is converted to estramustine, its active cytotoxic form, by dephosphorylation. Estramustine is a non-nitrogen mustard conjugated to estradiol through a carbamate ester bond. This linkage is not susceptible to cleavage (Punzi et al., 1992), and the parent molecule has antitumor activity through the binding and destabilizing of microtubules (Speicher et al., 1994) with resultant antimitotic activity (Sears et al., 1985). Its clinical utility has been extended through combination protocols with other antimicrotubule drugs (Speicher et al., 1992) to the treatment of hormone refractory prostate cancer, with a significant number of positive clinical trial results in the last few years (for example, see Hudes et al., 1992). In addition, because of the improved understanding of its pharmacology, the drug has proven its utility in the management of breast cancer (Hamilton and Muggia, 2001), glioblastoma (Rosenthal et al., 2000), and non-Hodgkins lymphoma (Borghaei et al., 2004). Although estramustine has an established clinical niche, investigators continue to expand its clinical utility and synthesize novel analogs (Nicholson et al., 2002).

In the rat, estramustine can be concentrated intracellularly through binding to the estramustine binding protein, a factor variously referred to as estramustine binding protein, steroid binding protein, prostatin, or prostatein (Forsgren et al., 1979). A similar process may occur in humans via structurally similar protein subunits, called lipophilins. Lipophilins A to C have been described as plausible human counterparts of the C1, C2, and C3 subunits of prostatin (Zhao et al., 1999). One component, lipophilin A, was homologous to the C1 and C2 subunits of rat prostatin, whereas the other, lipophilin C, was homologous to the C3 subunit and to human mammaglobin, a protein expressed in some breast carcinomas (Becker et al., 1998). These peptides are within the secretoglobin family, a group of proteins expressed in numerous secretory glands, including mammary, sweat, salivary, and other tissues.
Materials and Methods

Cell Culture. DU145 wild-type and estramustine-resistant cells (DU145 EM) were maintained in Dulbecco’s minimal essential media supplemented with 10% fetal calf serum (Mediatech, Herndon, VA), 2 mM l-glutamine, 0.1 mM nonessential amino acids, and 100 units/ml penicillin-streptomycin (Invitrogen, Carlsbad, CA). The media used to maintain estramustine-resistant DU145 cells contained 15 μM estramustine. PC3 wild-type and estramustine-resistant cells (PC3 EM) were maintained in F-12K Nutrient Mixture (Kgaithn’s modification; Mediatech) supplemented with 10% fetal calf serum and 100 units/ml penicillin-streptomycin. The media for the estramustine-resistant cells contained 10 μM estramustine. SKOV3 wild-type and estramustine-resistant cells (SKOVEM) were maintained in Alpha Modification of Eagle’s Medium (Mediatech) supplemented with 10% fetal calf serum, 2 mM l-glutamine, and 100 units/ml penicillin-streptomycin. SKOVEM cells were maintained in media containing 15 μM estramustine.

Analysis of Lipophilin Expression in Prostate Tumors. Six matched normal and tumor prostate tissue samples were obtained from the Fox Chase Cancer Center Tumor Bank Facility (Philadelphia, PA) and prepared and analyzed by personnel in accordance with the Fox Chase Cancer Center Institutional Review Board. Total RNA from these samples and total RNA from prostate cancer cell lines were isolated using the RNeasy Mini Kit (QIAGEN, Valencia, CA). Two micrograms of total RNA was DNase I treated (Invitrogen), 1 μg of which was used for cDNA synthesis, and the remaining RNA served as a negative control for RT-PCR. First strand cDNA synthesis was performed using Super Script II RNase H (Invitrogen), served as a negative control for RT-PCR. First strand cDNA synthesis was performed using Super Script II RNase H. Reverse Transcriptase (Invitrogen). cDNA was used as a template for PCR amplification (Advantage cDNA Polymerase Mix; BD Biosciences Clontech). cDNA was used as a template for PCR amplification (Advantage cDNA Polymerase Mix; BD Biosciences Clontech) with the Fox Chase Cancer Center Institutional Review Board. Total RNA of which was used for cDNA synthesis, and the remaining RNA served as a negative control for RT-PCR. First strand cDNA synthesis was performed using Super Script II RNase H (Invitrogen). cDNA was used as a template for PCR amplification (Advantage cDNA Polymerase Mix; BD Biosciences Clontech). cDNA was used as a template for PCR amplification (Advantage cDNA Polymerase Mix; BD Biosciences Clontech) with the Fox Chase Cancer Center Institutional Review Board. Total RNA of which was used for cDNA synthesis, and the remaining RNA served as a negative control for RT-PCR. First strand cDNA synthesis was performed using Super Script II RNase H (Invitrogen). cDNA was used as a template for PCR amplification (Advantage cDNA Polymerase Mix; BD Biosciences Clontech).

Cloning of Lipophilins B and C. The 5′ and 3′ ends of lipophilin B and C cDNA were generated using a rapid amplification of cDNA ends-PCR strategy. Full-length cDNAs were constructed using a sense primer beginning at the first nucleotide of the 5′ end of lipophilin C, and PsI restriction sites were present in both the 5′ and 3′ end overlapping fragments. Both fragments were cut with PsI, ligated, cloned into pCR-XL-Topo vector, and sequenced. For lipophilin B, overlap extension was performed for 3′ and 5′ end fragments and used as a template for PCR with the T7 universal primer (New England Biolabs, Beverly, MA). Both lipophilin B and C PCR products cloned into pCR-XL-Topo vector (Invitrogen) for sequencing. Sequence information for full-length lipophilin C cDNA, prepared as described above, was obtained from six normal and tumor samples.

For lipophilin B, primer mutagenesis was used to introduce a Kozak sequence, remove the stop codon, and create Nhel and BamHI restriction sites. Using these restriction sites, lipophilin B cDNA sequence was cloned in-frame with a C-terminal myc-His-tag into pCDNA3.1myc-His(−3′c vector (Invitrogen), further referred to as His-LB. For lipophilin C, primer mutagenesis was used to remove the start codon that was mutated, and an Xhol was generated. The PCR product was cloned into pCR-XL-Topo vector (Invitrogen) and subcloned into the pEGFP-C3 vector (BD Biosciences Clontech), using the created Xhol site and EcoRI site from the pCR-XL-Topo vector. The lipophilin C cDNA sequence was in frame with an N-terminal EGFP tag (EGFP-LC).

Transfection. DU145 and PC3 cells were transfected with the plasmid constructs EGFP-LC and His-LB, respectively, or vector alone controls, using 15 μl of FuGENE 6 Transfection Reagent (Roche Diagnostics, Indianapolis, IN). At 24 h post-transfection, the medium was replaced with serum-free medium, and at 60 h, medium was collected from transfected and vector-alone transfected cells, centrifuged at 500g for 10 min, and concentrated using Amicon Centriplus YM-10 for EGFP-LC or YM-3 for His-LB (Millipore Corporation, Billerica, MA).

Western Blotting. Cells were harvested with a cell scraper and homogenized using a syringe fitted with a 21-gauge needle. Cells were lysed in PBS containing 1% Nonidet P-40, 0.5% sodium deoxycholate, 0.1% SDS, 10 μg/ml phenylmethylsulfonyl fluoride, 30 μl/m of aprotinin (Sigma-Aldrich, St. Louis, MO), and 100 mM Na3VO4. Cell lysate was then incubated for 45 min on ice and centrifuged at 10,000g for 10 min at 4°C. The supernatant was collected, and protein concentrations were measured using the Bradford method (Bio-Rad). Proteins were separated on a 15% SDS-polyacrylamide gel and transferred to nitrocellulose membranes using an electrophoretic transfer apparatus (Bio-Rad). Membranes probed with anti-His antibody were blocked with 6% bovine serum albumin (Sigma-Aldrich) and 0.5% Tween 20 (Bio-Rad). Membranes probed with anti-EGFP were blocked in 5% nonfat dry milk/PBS/0.5% Tween 20 in Tris-buffered saline. Monoclonal anti-penta-His (QIAGEN) and polyclonal anti-EGFP (BD Biosciences Clontech) antibodies were diluted 1:1000 in blocking buffer. All antibodies were incubated at 25°C for 1 h or at 4°C for 16 h. Membranes were probed with horseradish peroxidase-linked secondary antibodies and detected using an enhanced chemiluminescence system (GE Healthcare, Little Chalfont, Buckinghamshire, UK) with Kodak film.

Cell Survival Assay. Estramustamine phosphate (EMP) in its disodium salt form (Emcyt; Pharmacia and Upjohn Company, Kalamazoo, MI) was dissolved in dimethyl sulfoxide (DMSO) and sterilized using a 0.22-μm DMSO-safe syringe filter (Pall Life Sciences, East Hills, NY). Cell viability following EMP exposure was measured in both parental PC3 cells and PC3 transfectants expressing EGFP-LC, referred to as clones A4, A6, C2, and D2. Cells cultured in RPMI 1640/10% fetal bovine serum (Invitrogen) were seeded at 7000 cells/well in a 96-well format and treated with EMP or DMSO vehicle control for 3 days. A colorimetric, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT)-based assay was used to quantify cell viability. MTT was added to the cells for a final concentration of 0.5 mg/ml. After a 4-h incubation at 37°C/5% CO2, cells were

TABLE 1

<table>
<thead>
<tr>
<th>cDNA</th>
<th>Primer Sequence (5‘-3’ )</th>
<th>Sequences (5‘-3’ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lipophilin A</td>
<td>Sense CATCATTGTTAAGCCGAG</td>
<td>Antisense AGATGTGGAAGACTCAGATT</td>
</tr>
<tr>
<td>Lipophilin B</td>
<td>Sense GCTGTAAGACTCTCTCTGATTGT</td>
<td>Antisense GGACTTCCGGAATGCGTCCTGT</td>
</tr>
<tr>
<td>Lipophilin C</td>
<td>Sense CTGCCAGCAGCACTGAACACAGAC</td>
<td>Antisense GTACACTGATGATCATGATACGTCAAA</td>
</tr>
</tbody>
</table>
permeabilized in 10% SDS/0.1 M HCl and incubated again for 16 h. Absorbance was measured on a Benchmark Microplate reader (Bio-Rad). Cell viability, as defined as the difference in absorbance at 550 and 690 nm, was determined for cell lines at various concentrations of EMP. IC_{50} values were determined using KaleidaGraph software (Synergy Software, Reading, PA).

Flow Cytometry. PC3 cells and pEGFP-lipophilin C-expressing clones were seeded on 10-cm plates, grown to ~80 to 90% confluence, harvested, counted using a hemocytometer, and pelleted by centrifugation at 4°C. After removing media, the cells were washed twice in ice-cold PBS and fixed in 2% paraformaldehyde/PBS, pH 7.4, for 1 h at 4°C. Cells were resuspended in PBS at 10^6 cells/ml for analysis on the FACSCalibur analytical flow cytometer (BD Biosciences Clontech). EGFP-positive cells were gated from a minimum of 10^4 cells per run. Data are reported as the average percentage of cells gated within the EGFP-positive population.

Statistics. Three independent experiments were conducted for analyses of data from RT-PCR, Western blotting, cell survival assays, and flow cytometry. For cell survival assays (n = 21 for each experiment) and RT-PCR densitometry (n = 3 for each experiment), a Student’s t test was used to compare mean values. Differences were considered to be significant if p values were less than 0.05. Linear regression analysis of mean EGFP expression versus mean IC_{50} values for EMP treatment was performed using QuickFit software (Micro-Active Australia Pty Ltd, Chermside, Australia).

Results

Lipophilins B and C Are Not Differentially Expressed in Human Prostate Tumors. The expression profiles of specific isoforms of human lipophilin were determined in both clinical prostate samples and in various human cancer cell lines. Using primers for RT-PCR analysis (Table 1), expression of lipophilins A to C in human clinical biopsies and cell lines from prostate were analyzed. Lipophilin A levels in all biopsy and cell line samples proved to be below the level of detection (data not shown), whereas lipophilins B and C (Fig. 1A) were expressed at detectable levels in both normal and tumor tissues. In the examples shown from four individuals (Fig. 1A), expression levels were variable, with some paired samples showing apparent differences in expression. However, quantitative analyses of replicates (n = 15) showed no statistical difference in expression levels between normal and tumor samples of all six patients (p > 0.05).

Lipophilin C Polymorphism in Prostate Tumors. Comparative sequence data for cDNAs from normal and malignant human prostate samples were analyzed to search for the presence of possible somatic mutations. No changes in lipophilin A or B were found (n = 6); however, for lipophilin C, a T to C transition was found in tumors at positions 409 and 412 (Fig. 1B). Samples from both normal and tumor tissues were shown to have an additional guanine residue at position 413 when compared with the GenBank sequence. This change was outside of the open reading frame.

Expression of Lipophilins in Cancer Cell Lines Is Unrelated to an Estramustine Resistance Phenotype. Lipophilin B was detected at equivalent low levels in both wild-type and estramustine-resistant DU145 and PC3 cells. Similar low levels were found in SKOV3 ovarian carcinoma cells and a line made resistant to estramustine, and there was no enhanced expression of lipophilin B in the resistant cell line (data not shown). Concurrent with the biopsy data, lipophilin C was also expressed at low levels in prostate carcinoma cells (PC3 and DU145) and their EM-resistant counterparts (Fig. 2). Similarly, SKOV3 ovarian carcinoma cells and corresponding EM-resistant clones (SKOVEM3, SKOVEM10, and SKOVEM15, each adapted to grow in 3, 10, and 15 μM EM, respectively) had no differences in lipophilin C expression (Fig. 2). Relative expression patterns for lipophilin C were confirmed by real-time PCR using 18S rRNA as a loading control (data not shown). Overall, drug resistance to EM did not seem to require modulation of lipophilin C expression by tumor cells, nor did it seem to be a cause and/or effect of malignant transformation.

Epitope-Tagged Lipophilins Are Not Secreted When Transiently Expressed in Prostate Cancer Cells. To study these secretory proteins, tagged constructs were generated to assess whether lipophilins were secreted into the extracellular medium in overexpressing cell lines. The pcDNA3.1/myc-His(−)lipophilin B construct was transfected into PC3 cells; after 60 h, the medium was collected for detection of any secreted protein, and cells were harvested and lysed for analysis of intracellular protein. The myc-His tag was detected in the cell lysates but not in the medium (Fig. 3A). Similarly, DU145 cells were transfected with the pEGFP-C3 lipophilin C plasmid, and the fusion protein was found in the lysate but not in the medium (Fig. 3B). However, EGFP alone was detected both in the cell lysates and in the medium of the cells transfected with the empty pEGFP-C3 vector (Fig. 3B). These results demonstrated overexpression of lipophilin B or C in PC3 or DU145 cells, respectively, and
suggested that neither isoform was secreted in this cellular context.

**Stable Expression of a Lipophilin C-EGFP Fusion Protein Did Not Consistently Impact PC3 Cell Response to EMP Treatment.** Subsequent treatment of the transfected cells with EMP showed that increased expression of the EGFP-lipophilin C fusion protein had no impact on cell survival (Fig. 4). IC₅₀ values for EMP treatment were calculated by the average of three independent experiments for EGFP-LC clones A4, A6, C2, and D2 and PC3 parental controls. Cell viability was quantified by colorimetric MTT assay following 3 days of EMP exposure. EGFP expression is shown by the average percentage of cells gated within the EGFP-positive population. Flow cytometric analysis was also conducted in triplicate. Linear regression analysis (Quick Fit) showed no correlation between EGFP expression and EMP IC₅₀ values ($r = 0.21$, $p = 0.73$).

**Discussion**

The aim of this study was to investigate what role, if any, lipophilins might play in determining the response of prostate cancer to the antimicrotubule drug estramustine. The clinical formulation, estramustine phosphate, is routinely used in the treatment of hormone refractory prostate cancer. Earlier reports have suggested that the efficacy of the drug in rats may be affected by the presence of prostatin (Forsgren et al., 1979). When homology between prostatin and lipophilin family members was described (Lehrer et al., 1998), there seemed to be value in comparing lipophilin expression patterns and drug response in biopsies and cell lines.

In the present study, two T to C transitions were found in the lipophilin C sequence of human prostate tumor biopsies that were not observed in matched normal tissues. These changes, outside of the open reading frame, did not appear to affect expression levels of lipophilin C because normal and tumor paired samples did not differ significantly. In prostate cancer cell lines, DU145 and PC3, clones with acquired EM resistance, expressed similar levels of lipophilins B and C versus parental controls. In addition, the overexpression of lipophilin C in PC3 cells did not alter the growth-inhibitory effects of estramustine.

Our earlier work showed that acquired resistance to estramustine was accompanied by amplification of the q34 region of chromosome 9, a region containing the ATP binding cassette transporter ABCA2 (Laing et al., 1998), a transporter that is causally linked with sequestration of drug into the endosome/lysosome compartment (Vulevic et al., 2001). The chromosomal localizations of lipophilin genes are 15q12-q13 (lipophilin A), 10q23 (lipophilin B), and 11q12-q13.1 (lipophilin C) (Lehrer et al., 2000). At least in this estramustine-selected resistant cell line, there is no concordance between resistance and those chromosomal regions coding for lipophilins. This fact would be consistent with the lack of any positive correlation described by the present data.

There are a number of explanations for the low expression levels of lipophilin B and C in the cell culture lines (DU145, PC3, and SKOV3). These cell lines are known to grow in a...
hormone-independent manner. DU145 and PC3 cells are androgen receptor negative (Chleksni et al., 2001) and do not bind testosterone. In SKOV3, androgen and progesterone receptors are dramatically down-regulated, and estrogen receptor α is mutated (32-base pair deletion in exon 1), defining SKOV3 as estrogen receptor-positive but estrogen-insensitive (Lau et al., 1999). The expression of C3 and C1 subunits of rat prostate is regulated by androgen (Zhang et al., 1988). These findings, together with in vitro androgen receptor binding to DNA sequences from intron 1 of the C3(1) gene of prostatic binding protein. Biochim Biophys Acta Commun 164: 823–830.


Acknowledgments

We thank Richard Peppler (Flow Cytometry Core Facility at the Medical University of South Carolina) for technical assistance with data collection and analysis.

References

