Loss of PTEN Permits CXCR4-Mediated Tumorigenesis through ERK1/2 in Prostate Cancer Cells

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Abstract

Loss of PTEN is frequently observed in androgen-independent prostate cancer, resulting in the deregulation of metastatic events. SDF1α activation of CXCR4 induces signaling pathways that have been implicated in prostate metastasis and progression to an advanced disease. The pathways of CXCR4 and PTEN converge, leading to the promotion and regulation of tumorigenesis, respectively. However, loss of PTEN may permit CXCR4 to progress prostate cancer to an advanced disease. In the present study, we investigated the involvement of PTEN in CXCR4-mediated tumorigenesis. When screening advanced metastatic prostate cancer cell lines for PTEN, we observed a loss of expression in PC3 and LNCaP cells whereas Du145 expressed wild-type PTEN. All three cell lines were positive for surface expression of CXCR4. Reconstitution of PTEN induced a mesenchymal to epithelial like morphologic change and inhibited CXCR4-mediated migration and proliferation in PC3 cells. Downregulation of PTEN by siRNA enhanced the CXCR4-mediated migratory behavior of Du145 cells. By Western blot analysis, we observed that PTEN inhibited basal AKT phosphorylation but not ERK1/2 phosphorylation in PTEN-expressing cells. Upon CXCR4 stimulation, PTEN inhibited ERK1/2 phosphorylation but not phosphorylation of AKT. The CXCR4-mediated migration of PC3 cells was through the ERK1/2 pathway, as confirmed by chemical inhibitors. On the basis of these studies, we suggest that loss of PTEN permits CXCR4-mediated functions in prostate cancer cells through the ERK1/2 pathway. Antagonizing CXCR4 and downstream signaling cascades may provide an efficient approach for treating patients with advanced prostate cancer when hormone therapy fails to stop the growth and containment of tumors.

Introduction

The relative 5-year survival rate among prostate cancer survivors is nearly 100%, versus a 15-year relative survival rate of 76% (1). Improved treatments and methods of detection have translated into prostate cancers being both found earlier in their development and treated more effectively. Despite these advances, prostate cancer still accounts for approximately 10% of cancer-related deaths in men (1). Prostate cancer growth is dependent upon increasing levels of androgens, which stimulate the growth, survival, and function of cells that express the androgen receptor. During the early stages of prostate cancer, hormone deprivation therapy proves to be effective. However, advanced prostate tumors grow accustomed to androgen depletion, circumventing restraints on growth and movement, and eventually develop metastatic colonies in the bones and other distal organs.

Progression to androgen insensitivity is mediated largely by androgen receptors (AR); however, this process is distinct from metastatic progression, where tumor suppressors fail to regulate signals that influence cell adhesion, anchorage, and movement (2). Genomic deletions in the tumor suppressor PTEN are common in androgen-insensitive prostate tumors, although the incidence and its downstream effects have not been well elucidated in clinical samples of hormone refractory prostate cancers. Loss of PTEN is well documented in prostate cancer and cancer overall and seems to act as a permissive event for uncontrollable cell proliferation, invasion, and metastasis (3–6).

Although PTEN haploinsufficiency is strongly correlated with the conversion of a high-grade prostatic intraepithelial neoplasia (PIN) to an invasive adenocarcinoma, the underlying mechanisms permitting ensuing invasion and metastasis are poorly understood (3, 7).

PTEN functions as a dual-specificity lipid and protein phosphatase that inhibits cell proliferation, survival, and growth, predominantly through dephosphorylation of phosphatidylinositol 3,4,5-trisphosphate (PIP3), thus antagonizing phosphatidylinositol 3-kinase (PI3K)/protein kinase B (AKT)-mediated signaling events (8). By converting PIP3...
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wallace et al. showed that prostate tumors could carry alleles that contribute to advanced, metastatic stages of prostate cancer; CXCR4 was among the genes with elevated levels of expression (13). The chemokine receptor CXCR4 and its ligand stromal cell-derived factor 1 alpha (SDF1α or CXCL12) play a crucial role in targeting solid tumor metastases to sites outside of the primary tumor. CXCR4 has become a potential target for therapeutic intervention in malignancies that metastasize (14); a study by Akashi et al. revealed that CXCR4 expression was higher in malignant prostate tumors than in their normal healthy counterparts, suggesting that its expression level correlated with increased metastasis-associated mortality (15). Positive expression of CXCR4 has become a superior predictor of tumor aggressiveness, poor prognosis, and prostate cancer bone metastasis (16, 17). Upon SDF1α binding to CXCR4, the activation of metastasis-associated pathways makes this receptor favorable to tumorigenesis: (i) G-protein-coupled receptor (GPCR) signaling, (ii) PI3K/AKT, (iii) MAPK, (iv) JAK/STAT, (v) Src kinase, and (vi) HER2 (12, 18, 19).

Downstream, CXCR4-initiated signaling leads to cell polarization, an initial step in metastasis, and the transcription of genes involved in migration (14). It has been reported that CXCR4 was expressed on the surface of prostate cancer cells and was involved in facilitating prostate metastasis (16–18).

Independently, PTEN and CXCR4 have been noted for their involvement in prostate cancer invasion, metastasis, and progression. PTEN alterations are strongly implicated in prostate cancer development, placing the tumor suppressor high among the most common genetic alterations in human prostate tissues (8, 20, 21). PTEN deletions and/or mutations are found in up to 30% of primary prostate cancers and 60% to 63% of metastatic prostate tissues (21–23). Functionally, loss of PTEN developed prostatic neoplasia into an advanced, metastatic state (3), and correlated with increased prostate cancer cell migration toward bone-conditioned medium (24). Conversely, reconstituted PTEN in prostate cancer cells controlled migration (25) and conferred sensitivity to chemotherapy (26). Collectively, these data establish PTEN as an essential tumor suppressor in the prostate. Therefore, the absence of PTEN may contribute to a tumor environment that is conducive to prostate cancer development and progression.

To date, one link has been established between CXCR4 and PTEN in inflammatory chemotaxis, where PTEN inhibited movement of Jurkat cells stimulated with SDF1α (27). In non–small cell lung cancer, Phillips et al. observed that PTEN blocked hypoxia-induced expression of CXCR4 (28). Likewise, in prostate cancer, Carver et al. (7) observed a correlation in expression between PTEN and CXCR4; however, neither study reported a functional relationship.

To our knowledge, a functional relationship between PTEN and CXCR4 has not been established in prostate cancer. Therefore, our aim was to determine whether loss of PTEN in prostate cancer cells provides a “permissive switch” for CXCR4-mediated signaling and functions, as upregulation of CXCR4 is associated with the development of an advanced disease.

Materials and Methods

Cell culture, antibodies, and reagent conditions

LNCaP, PC3, Du145 human prostate cancer cell lines, and 293T human embryonic kidney cell line were obtained from American Type Culture Collection. C42 human prostate cancer cells were a kind gift from Dr. Leland Chung, Cedars-Sinai Medical Center, Los Angeles, CA. All cells were maintained in RPMI 1640 containing 10% FBS, 1% nonessential amino acids and 1% antibiotic-antimycotic at 37°C in 5% CO2, or starvation media (RPMI). All cells were maintained at 60% to 80% confluency. PD98059 was from Sigma Aldrich; LY294002 was from Cayman Chemicals; cell culture supplies were from MediaTech; and SDF1α was from PeproTech. The following human antibodies were from Cell Signaling: anti-PTEN, anti-AKT, anti-phospho-AKT (p-AKT), and anti-phospho-ERK1/2 (p-ERK1/2). Anti-ERK1/2 was from Biosource; β-actin, anti-GFP, and Fusin-CXCR4 were from Santa Cruz Biotech.

Plasmid construct

PTEN (pcDNA3-GFP-PTEN) and GFP (pcDNA3-GFP) constructs were generated as described previously (19). Briefly, GFP (green fluorescent protein) was cloned into the 5' end of pcDNA3 plasmid (Invitrogen), using HindIII and BamHI restriction enzyme sites to generate pcDNA3-GFP. The coding sequence for human PTEN was cloned into BamHI and EcoRI restriction sites of pcDNA3-GFP in order to generate pcDNA3-GFP-PTEN.

Western blot analysis

Cells were grown on 10-mm dishes, washed with 1× PBS, and harvested in lysis buffer containing 20 mmol/L Tris-HCl (pH 7.5), 150 mmol/L NaCl, 1 mmol/L Na2EDTA, 1 mmol/L EGTA, 1% Triton, 2.5 mmol/L sodium pyrophosphate, 1 mmol/L β-glycerophosphate, 1 mmol/L Na3VO4, 1 μg/mL leupeptin, and 1mmol/L PMSF (Cell Signaling). Protein concentrations were estimated using Bradford protein assay (BioRad). Equal concentrations of total cell lysate were resolved by 10% SDS-PAGE and transferred to a polyvinylidene fluorde (PVDF) transfer membrane. Nonspecific binding sites were blocked with 5% nonfat dry milk/0.1% Tween 20/1× TBS, followed by an incubation with primary antibodies for the proteins of interest in 3% bovine serum albumin–Tris-buffered saline Tween 20 (BSA-TBST; p-ERK1/2, p-AKT, AKT, PTEN) or 3% nonfat dry milk-TBST (ERK1/2).
Membranes were washed in 1× TBST and incubated in horseradish peroxidase–conjugated anti-rabbit (p-ERK1/2, p-AKT, AKT, PTEN) or anti-mouse secondary antibodies (ERK1/2; 1:10,000; Jackson ImmunoResearch) in 3% BSA-TBST or 3% nonfat dry milk-TBST for 1 hour at room temperature. Immunoblots were visualized using Super Signal West Pico Chemiluminescence reagent (Thermo Scientific).

**PCR amplification**

Total RNA was isolated with Total RNA Kit-I (Omega Bio-TeK), as described by the manufacturer. It was reversed transcribed with M-MLV Transcriptase (Promega) to generate cDNA for PCR amplification. Specific sense and antisense primers for PTEN, and housekeeping gene L19, were synthesized by Integrated DNA Technologies as follows: PTEN (forward GGA CGA ACT GGT GTA ATG ATA TG; reverse TCT ACT GTT TTT GTG AAG TAC AGC) and L19 (forward GAA ATC GCC AAT GCC TG; reverse TCT TA ACC TC GAG CAG CCT CA).

**Flow cytometric analysis**

Cells (1 × 10⁶) were plated in 100-mm dishes and serum starved overnight for synchronization, before treating with SDF1α. Cells were detached with 1× citric saline and fixed in 4% paraformaldehyde at 4°C for 30 minutes. Cells were washed in 1× PBS, followed by centrifugation at 3,000 rpm. Nonspecific binding sites were blocked in blocking buffer (1% donkey serum in 1× PBS) at 4°C for 1 hour, followed by an incubation overnight in CXCR4 antibody (1:100) in blocking buffer at 4°C or without antibody (control). Cells were washed once in 1× PBS, followed by incubation in fluorescein isothiocyanate (FITC) or indocarbocyanine (Cy3) fluorophore-conjugated secondary antibodies (1:500; Jackson ImmunoResearch) in blocking buffer at 4°C for 45 minutes. Cells were washed and resuspended in 1× PBS, and the surface expression of CXCR4 was analyzed by flow cytometry (Accuri C6). Results were quantified using GraphPad Prism 5 statistical software.

**Transient transfection**

Transient transfections of pcDNA3-GFP or pcDNA3-GFP-PTEN were carried out in PC3 cells by using Lipofectamine 2000. Briefly, cells (5 × 10⁵) were plated in 100-mm dishes and transfected with 100 μM PTEN-siRNA or scramble-siRNA (Santa Cruz) in starvation media at 37°C in 5% CO₂ for 24 hours. Transfected cells were harvested for Western blot analysis or a migration assay.

**Immunocytochemistry**

Cells (5 × 10⁵) were plated on glass slips in each well of a 10-mm plate. Cells were washed with 1× PBS, fixed with 4% paraformaldehyde, washed twice for 5 minutes in Tris-glycine (0.1 mol/L glycine, pH 7.4), and followed by a wash in 1× PBS. Nonspecific binding sites were blocked in blocking buffer (5% normal donkey serum, 1% BSA, 0.1% Tween 20 in PBS) for 30 minutes, followed by incubation overnight with CXCR4 antibody (1:100) in blocking buffer at 4°C. Cells were washed three times with 1× PBS, followed by an incubation in Cy3-conjugated secondary antibody (1:500) in blocking buffer for 45 minutes in the dark at room temperature. Cells were washed twice in 1× PBS, followed by incubation in 4’6-diamidino-2-phenylindole (DAPI; Sigma; 1:500 in PBS) for 1 minute. Glass coverslips were washed in 1× PBS before mounting on microscope slides with AquaPolymount (Polysciences, Inc.). Fluorescence was analyzed by using a Zeiss Axio Imager.z1 fluorescence microscope.

**[³H]Thymidine incorporation**

Cells were plated at a density of 4 × 10⁴ cells per well in 24-well culture plates and transfected with pcDNA3-GFP or pcDNA3-GFP-PTEN plasmids as described previously. Cells were serum starved for 24 hours before incubating with 100 ng/mL of SDF1α at 37°C in 5% CO₂. At each time point (24 and 48 hours), the media was replaced with RPMI containing 100 ng/mL of SDF1α, were added to the upper Transwell chamber. RPMI containing 100 ng/mL of SDF1α was added to the lower chamber, and cells were allowed to migrate toward SDF1α in the lower chamber for 4 to 6 hours at 37°C. Cells that remained in the upper chamber were removed with a cotton swab, fixed, and stained with Hemacolor Solution 3 Kit (EMD). Migrated cells were counted using a Zeiss Axiovert 200M light microscope. Results were quantified using GraphPad Prism 5 statistical program.
containing 1 μCi/mL of [3H]thymidine (PerkinElmer) and cells were incubated for 4 hours at 37°C. Cells were sonicated and filtered through Whatman DE81 filter paper discs, using a vacuum pump, before measuring the filter discs for radioactivity incorporation using a LS6500 multipurpose scintillation counter (Backman Coulter). Results were quantified using GraphPad Prism 5 statistical program.

Statistics and quantifications
Data are presented as the mean ± SE of at least 3 independent experiments and were analyzed by 2-way ANOVA or Student’s t test. All statistical analyses were done, and all graphs generated, using GraphPad Prism 5.0 software (GraphPad).

Results
PTEN was differentially expressed, whereas reconstitution of PTEN induced morphologic changes in prostate cancer cells
On the basis of the reports that PTEN haplosufficiency is strongly correlated with the conversion of prostate tumors to an invasive adenocarcinoma (3, 7), and the observations that CXCR4 is highly expressed in advanced prostate tissues (17, 30), we surmised that the absence of PTEN permits CXCR4-mediated functions and development of an aggressive phenotype in prostate cancer. We compared the levels of PTEN expression among prostate cancer cell lines (PC3, LNCaP, C42, and Du145) by Western blot and RT-PCR assays. PTEN was expressed at both the protein and mRNA levels in androgen-independent Du145 cells and positive control human embryonic kidney cells, 293T (Fig. 1A). Protein (Fig. 1A), but not mRNA (Fig. 1B), PTEN expression was absent in androgen-dependent LNCaP and androgen-independent C42 cell lines (Fig. 1A). Genetic studies have shown that Du145 cells carry one functional PTEN allele whereas the other allele is deleted (31). LNCaP cells carry a base pair deletion found on codon 6 of PTEN, inhibiting translation (31). C42 cells are a metastatic derivative of LNCaP isolated from the bone (32). Finally, PTEN was not detected in androgen-independent PC3 cells at both the protein and mRNA levels, due to homologous deletions of the PTEN gene (Fig. 1A and B) (31). The PTEN expression profiles observed in PC3, LNCaP, and Du145 cells are concurrent with previously published data (33).

Figure 1. Expression profiles of CXCR4 and PTEN in PC3 and LNCaP prostate cancer cells. A, 40 μg of total protein was analyzed for PTEN expression by Western blot analysis, using a PTEN specific antibody. Total ERK1/2 served as a loading control. B, 2 μg of total RNA was isolated and reverse transcribed to cDNA for PCR amplification, using primers specific for PTEN. L19 served as a loading control. C, PC3, LNCaP, and Du145 cells were fixed in 4% paraformaldehyde, blocked in 1% donkey serum/PBS, and probed with a CXCR4-specific antibody. CXCR4 was detected with a FITC-conjugated donkey anti-mouse antibody. Cells were analyzed for FITC fluorescence intensity, using an Accuri C6 flow cytometer. D, mean fluorescence was quantified and graphed to represent fold change. Experiments were repeated thrice, and the data are presented as fluorescence fold change over control. E, pcDNA3-GFP (PC3-GFP) and pcDNA3-GFP-PTEN (PC3-PTEN) constructs were transiently transfected into PC3 cells, before fixing with 4% paraformaldehyde, blocking in 1% donkey serum/PBS, and probing with a CXCR4-specific antibody. CXCR4 was detected with a Cy3-conjugated donkey anti-mouse antibody prior to analysis for Cy3 fluorescence intensity by flow cytometry.

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CXCR4 is expressed in various cancer models, including prostate (18). We compared the cell surface expression of CXCR4 in PC3, LNCaP, and Du145 cells by flow cytometric analysis. PC3, LNCaP, and Du145 cells were chosen for this assessment because PC3 and LNCaP are absent for PTEN protein and Du145 cells express functional PTEN. Because PC3 cells are representative of an androgen-independent model, C42 cells were excluded. Prostate cancer cells were fixed, incubated with a rabbit antibody against PTEN, and analyzed for FITC intensity by flow cytometry. We found that CXCR4 was expressed on the cell surface of all 3 cell lines, as detected by the positive shift in fluorescence (redline) compared with background control (black line; Fig. 1C). Quantitatively, these data revealed a 5-fold increase in overall fluorescence intensity of CXCR4 over background (control) in PC3 cells whereas LNCaP and

Figure 1. (Continued)
F, immunofluorescent images of PC3-GFP and PC3-PTEN cells. Cells were probed with a CXCR4 (red)-specific antibody. Nuclei were stained with DAPI (blue). Cont, control; *, P < 0.05.
Du145 cells revealed an increase of 20- and 15-folds, respectively (Fig. 1D). These values were standardized against the values of the background (control), which contained secondary antibody only.

Although a functional relationship has not been elucidated, Carver et al. observed a correlation in expression between PTEN and CXCR4 in prostate cancer (7). To address this relationship, PTEN expression was reconstituted in PC3 cells, as they are androgen-independent and highly metastatic and represent an advanced stage of prostate cancer. We generated PC3 clones transiently transfected with PTEN (pcDNA3-GFP-PTEN) or GFP (pcDNA3-GFP). Expression of PTEN did not affect the surface expression of CXCR4 in PC3 cells (Fig. 1E), nor did PTEN expression affect the diffuse subcellular localization of CXCR4, compared with control (Fig. 1F). Interestingly, we observed a morphologic change in PC3-PTEN cells compared with PC3-GFP cells, 48 hours posttransfection. Both PC3 and PC3-GFP cells showed a mesenchymal like morphology, as represented by lamellipodia-like projections (Fig. 2A). However, PC3-PTEN cells showed an epithelial like morphology compared with PC3 and PC3-GFP cells (Fig. 2A). In agreement with our observations, Kotelevets et al. observed that canine kidney epithelial cells transfected with PTEN retained an epithelioid morphotype compared with fibroblast-like cells transfected with PTEN mutants (34). To further investigate this morphologic transition, we analyzed the expression pattern of vimentin, an EMT marker (Fig. 2D). We found that vimentin expression decreased in PC3-PTEN cells compared with PC3-GFP cells. Copy DNA constructs were labeled with GFP; therefore, we utilized fluorescence microscopy to confirm that PTEN was expressed in these epithelial like cells. We detected GFP-PTEN fusion protein at the cell membrane of PC3-PTEN cells, where it primarily functions (Fig. 2B). To ensure that cDNA constructs were expressing the fusion protein, we detected PTEN expression by Western blot analysis (Fig. 2C).

PTEN expression inhibited CXCR4-mediated migration and proliferation of prostate cancer cells

Prostate cancer tends to spread to the bones. The CXCR4/SDF1α signaling axis was shown to play a pivotal role in triggering prostate bone metastasis (19), whereas Wu et al. observed that PTEN inhibited C42 cell migration toward calvaria-conditioned medium (24). To examine whether PTEN negatively regulates CXCR4-mediated migration and proliferation, respective assays were carried out with PC3, PC3-GFP, or PC3-PTEN cells upon CXCR4 stimulation with its ligand, SDF1α. By Transwell

**Figure 2.** Transient transfection of PTEN into PC3 cells induced a mesenchymal to epithelial like morphologic change. A, cells were transiently transfected with pcDNA3-GFP and pcDNA3-GFP-PTEN constructs. Light micrographs were taken 48 hours posttransfection at 10× magnification, using a Zeiss Axiovert 200M fluorescence microscope. B, transiently transfected cells were analyzed for GFP fluorescence 48 hours posttransfection. Cells were excited at 495 nm and micrographs were taken at 10× magnification, using a Zeiss Axiovert 200M fluorescence microscope. C, 30 μg of total protein was extracted from 2 clones of transfected cells and analyzed by Western blot analysis, using anti-PTEN and anti-GFP specific antibodies. β-Actin served as a loading control. D, transiently transfected cells were lysed and 30 μg of protein was analyzed for vimentin. β-Actin served as a loading control. Graph represents the relative expression of vimentin compared with control. *, P < 0.05.
assay, we observed an increase in cell migration of PC3 and PC3-GFP cells toward SDF1α in the bottom chamber (Fig. 3A). However, SDF1α failed to stimulate movement of PC3-PTEN cells (Fig. 3A), resulting in a significant reduction in cell migration compared with PC3 and PC3-GFP cells (Fig. 3B).

To further investigate the regulatory role of PTEN in CXCR4-mediated functions, PC3, PC3-GFP, and PC3-PTEN cells were analyzed for proliferation and viability. By MTT assay, we observed increases in the viability of both PC3 and PC3-GFP cells 48 hours posttreatment with SDF1α. However, the viability of PC3-PTEN cells was significantly reduced compared with PC3-GFP cells at both 24 and 48 hours post–SDF1α treatment (Fig. 3C). By [3H]thymidine incorporation assay, we observed increases in proliferation in both PC3 and PC3-GFP cells 48 hours post–ligand treatment, whereas the proliferation of PC3-PTEN cells was significantly reduced compared with PC3-GFP cells up to 48 hours post–SDF1α treatment (Fig. 3C).

Suppression of ERK1/2 phosphorylation inhibited CXCR4-mediated migration of PC3 cells

PTEN functions as a dual protein and lipid phosphatase. The major known substrate of PTEN is the lipid second
Figure 4. PTEN inhibited CXCR4-mediated migration by inhibiting ERK1/2 phosphorylation. A, transiently transfected cells were lysed and 30 μg of protein was analyzed for PTEN, p-AKT, total AKT, p-ERK1/2, and total ERK1/2 expression by Western blot analysis, using specific antibodies. Graph represents a densitometric analysis for the relative expression of p-AKT and p-ERK1/2 compared with controls. B, transiently transfected cells were treated with 100 ng/mL of SDF1α for 10 minutes followed by Western blot analysis of 30 μg of protein, using p-AKT, total AKT, p-ERK1/2, and total ERK1/2 specific antibodies. Graph represents a densitometric analysis for the relative expression of p-AKT and p-ERK1/2 compared with controls. PC3 (C) and PC3-GFP (E) cells were serum starved prior to treatment with 50 mmol/L of PD98059 and/or 10 mmol/L of LY294002 for 1 hour at 37°C. Cells were then stimulated with 100 ng/mL of SDF1α for 10 minutes followed by Western blot analysis of 30 μg of protein, using p-AKT, total AKT, p-ERK, and total ERK1/2 specific antibodies. PC3 (D) and PC3-GFP (F) cells were serum starved and treated with 50 μmol/L of PD98059 and/or 10 μmol/L of LY294002 for 1 hour at 37°C. Cells (2 × 10⁴) were added to the upper Transwell chamber and allowed to migrate toward 100 ng/mL of SDF1α in the lower wells for 6 hours at 37°C. Five fields were randomly selected and counted for migrated cells at 10× magnification. Experiments were repeated thrice, and data represent the averages of 3 independent experiments. *, P < 0.05.
messenger PIP₃, which activates downstream signaling components, most notably the protein kinase AKT (35). The subsequent activation of CXCR4/SDF1α involves classical pathways of cell survival: (i) PI3K/AKT; (ii) the MAPK cascade, and (iii) PLC-β (36). Many reports have observed AKT activation in response to SDF1α, whereas others have observed that ERK1/2 activity is required for GPCR-mediated migration (37, 38). When we investigated the basal levels of ERK1/2 and AKT in PC3-GFP and PC3-PTEN cells, we observed a decrease in phospho-AKT expression in PC3-PTEN cells compared with PC3-GFP cells (Fig. 4A). Phospho-ERK1/2 levels did not change (Fig. 4A). Treatment of serum-starved PC3-GFP and PC3-PTEN cells with SDF1α resulted in ERK1/2 phosphorylation in a biphasic manner, while no changes in AKT phosphorylation were observed compared to control (Fig. 4B). Phospho-ERK1/2 was detected in PC3-GFP cells upon SDF1α stimulation but not in PC3-PTEN cells under the same conditions (Fig. 4B).

To determine whether PTEN-mediated inhibition of ERK1/2 phosphorylation was responsible for the decreased CXCR4-mediated cell migration of PC3-PTEN cells, we used PD98059, a small molecule MEK inhibitor to suppress ERK1/2 phosphorylation, and LY294002, a small molecule PI3K inhibitor to suppress AKT phosphorylation. Pretreatment with PD98059 for 1 hour abrogated SDF1α-induced phosphorylation of ERK1/2 whereas LY294002 abrogated phosphorylation of AKT (Fig. 4C). Because we observed that PTEN blocked SDF1α-induced phosphorylation of ERK1/2, we then determined whether ERK1/2 abrogation inhibited CXCR4-mediated migration of PC3 cells. We monitored Transwell cell migration of PC3 and PC3-GFP cells toward SDF1α in the presence and absence of LY294002 and PD98059. Pretreatment with PD98059 significantly inhibited PC3 and PC3-GFP migration, which was not inhibited by LY294002 (Fig. 4D and F). Neither PD98059 nor LY294002 was cytotoxic to the cells (data not shown).

**Downregulation of PTEN expression enhanced CXCR4-mediated migration of Du145 cells**

PTEN inactivation correlates with invasiveness and metastasis in prostate cancers. Loss of PTEN is common in prostate cancers that have transitioned to an advanced disease. Du145 cells have low-to-moderate metastatic potential and express a functional PTEN allele. Therefore, we tested whether downregulation of PTEN could serve as the permissive switch for CXCR4-mediated migration. We utilized siRNA to downregulate the expression of PTEN in Du145 cells. Cells transfected with a fluorescein-conjugated siRNA targeted for PTEN or control (scramble siRNA) were subjected to a Transwell migration assay toward SDF1α. Clones transfected with PTEN siRNA exhibited decreased PTEN expression by Western blot analysis (Fig. 5A) and a significant increase in migratory activity toward SDF1α (Fig. 5B), which was not observed in control transfected cells. These findings suggest that there is a reciprocal relationship between CXCR4 activity and PTEN expression. Taken together, these results support the idea that the loss of PTEN regulation permits the advancement of prostate cancer through CXCR4 and its concomitant pathways.

**Discussion**

A physical interaction between PTEN and CXCR4 has not been elucidated. Upon SDF1α binding to CXCR4, pathways associated with tumorigenesis are activated: (i) GPCR signaling, (ii) PI3K/AKT, (iii) MAPK, (iv) JAK/STAT, (v) Src kinase, and (vi) HER2 (12, 18, 19). Downstream, CXCR4-initiated signaling leads to the transcription of genes involved in migration and tumorigenesis (14). Traditionally, PTEN functions as a dual-specificity lipid and protein phosphatase inhibits tumorigenic events through dephosphorylation of PIP3, thus antagonizing PI3K/AKT-mediated signaling (8). By converting PIP3 into PIP2, PTEN negatively regulates PI3K/AKT signaling and subsequent downstream pathways. PTEN and CXCR4 converge at the PI3K/AKT and/or MAPK signaling level. This is supported by our research.
and others, which indicates that PI3K/AKT and/or ERK inhibitors mimicked PTEN effects of negatively regulating CXCR4 (27). Therefore, our research describes that the loss of PTEN expression provides a "permissive switch" for CXCR4-mediated signaling and functions (Fig. 6).

In this report, we investigated PTEN in null human PC3 and wild-type human Du145 prostate cancer cell lines to characterize the involvement of PTEN in CXCR4-mediated functions. Our findings were as follows: i) PTEN-null PC3 cells exhibited potent CXCR4-mediated migration, indicating that PTEN was not essential for the movement of prostate cancer cells. (ii) By transient transfection, we found that reconstitution of PTEN expression in PC3 cells induced morphologic changes and down-regulated CXCR4-mediated migration and proliferation; (iii) PTEN reconstitution regulated phospho-ERK1/2 but not phospho-AKT in CXCR4-mediated functions. This was further supported by the observation that MAPK inhibitors mimicked PTEN effects of negatively regulating CXCR4-mediated migration. (iv) Expression of PTEN did not affect cell surface expression of CXCR4, suggesting that inhibition of CXCR4-mediated migration and proliferation was at the level of signaling. (iv) Down-regulation of wild-type PTEN by siRNA in Du145 cells increased CXCR4-mediated migration. Collectively, these findings indicate that the loss of PTEN expression in prostate cancer cells provides the loss of a critical inhibitory function in the signal cascade(s) that leads to cell migration and may provide the permissive switch to CXCR4-mediated tumorigenesis and advanced stages of prostate cancer.

Prostate cancers have the ability to localize to tissue sites throughout the body. Loss of tumor suppressors, specific chemotactants, and migration-promoting signaling pathways may influence sites of specific distant tumor formation. The long-held view is that metastasis occurs by a multistep process requiring intravasation, cell survival in the blood stream, extravasation, initiation of micrometastasis, and the establishment of new blood vessels (39). It has been proposed that the expression, or absence, of particular genes in primary tumors may directly predispose cancer cell growth and metastatic development. Aberrant expression of key genes, including CXCR4 and PTEN, has been established to collectively facilitate cell invasion, bone metastasis, cell adhesion, and angiogenesis (12, 16, 22, 40–43). CXCR4 and PTEN are independently identified as gene expression signatures, which reflect the activation status of oncogenic pathways, and, in turn, provide clinically relevant associations with disease outcomes (4, 44).

The potential prognostic role of the combined alterations in CXCR4 and PTEN in prostate cancer is not well established. A gene expression signature for immunohistochemistry-detectable PTEN loss has been developed for breast cancer, which correlates with poor patient outcome in independent data sets of breast, bladder, and prostate carcinoma (45). Primary prostate cancers often show genetic loss or mutation of at least one PTEN allele in approximately 30% to 70% of advanced (locally advanced or metastatic) cases, primarily at the level of transcription (46, 47). Conversely, in Du145, LNCaP, and PC3 prostate cancer cells, CXCR4 mRNA expression was approximately 1,000, 400, and 21 times, respectively, that of primary and normal prostate cancer cell lines 1542 NPTX, Pre 2.8, and 1542 CPT3X (48). In the same study, migration of the metastatic cell lines PC3 and Du145 was enhanced by SDF1α ligand and inhibited by an antibody to CXCR4, indicating that migration of metastatic prostate cancer cells was facilitated and enhanced by the SDF1α/CXCR4 signaling axis, which did not influence the migration of the normal prostate epithelial cells (48). Considering the converging pathways that CXCR4 and PTEN activate and inhibit, respectively, loss of PTEN could provide one of the critical events in human prostate cancer that cooperates to promote tumor development and progression through CXCR4.

Figure 6. Proposed mechanism for the role of PTEN in CXCR4-mediated signaling. A, ligand activation of CXCR4 stimulates several pathways, including PI3K/AKT and ERK1/2, resulting in tumorigenic events. PTEN negatively regulates both pathways by acting as a protein and lipid phosphatase. B, loss of PTEN expression results in a loss of regulation of CXCR4-mediated events, permitting activation of signaling pathways that enhance tumorigenesis.
There have been few studies on the role of PTEN in the metastatic events of prostate cancer. PC3 cells transfected with wild-type PTEN reverted the invasive phenotype and invasion of collagen type I (34). Wu et al. proposed that PTEN loss upregulated cell-cycle genes, cdcl6 and cyclin E2, which, in turn, lead to metastatic colonization at distant sites (4). In defining a relationship with PTEN, Carver et al. observed that cancer specimens containing chromosomal translocations involving the ERG locus were concomitant with the loss of PTEN expression and upregulation of CXCR4 in prostate cancer (7). Phillips et al. reported that overexpression of wild-type PTEN in non–small cell lung cancer cells inhibited hypoxia-induced CXCR4 expression (28).

Outside of prostate cancer, one group has studied the role of PTEN and CXCR4 in the chemotactic movement of PTEN-null Jurkat cells, where enhanced chemotaxis was observed. Induction of PTEN expression downregulated Jurkat cell chemotaxis toward SDF1α, which correlated with the reconstitution of PTEN expression. In the studies by Gao et al., they observed that lipid phosphatase activity of PTEN was essential for the role of PTEN as a negative regulator of chemotaxis, suggesting that PI3K pathway was involved and that PTEN antagonized PI3K to inhibit chemotaxis (49). In agreement with Gao et al., we observed downregulation of CXCR4-mediated migration and proliferation upon reconstitution of PTEN into PC3 cells. We also observed an increase in CXCR4-mediated migration of poorly migratory DU145 cells, upon down-regulation of PTEN by siRNA.

PTEN functions as a dual-functional protein and lipid phosphatase. Physiologically, PI3P is the substrate of PTEN, whereby PTEN dephosphorylates PIP3, indirectly inhibiting AKT activation. We found that phospho-ERK1/2, but not phospho-AKT, showed biphasic expression in PC3-PTEN cells following SDF1α stimulation. We further examined the roles of the ERK1/2 and AKT pathways in CXCR4-mediated migration by chemical impairment with PD98059 (MEK inhibitor) and LY294002 (PI3K inhibitor). Unlike LY294002, PD98059 inhibited CXCR4-mediated migration, further implicating a role for ERK1/2 in CXCR4-mediated metastasis. Corroborating our studies, Sun et al. observed that CXCR4-mediated chondrosarcoma cell invasion was inhibited by the CXCR4 inhibitor AMD3100, as well as with ERK1/2 inhibitor U0126 and ERK1/2 siRNA (50). Likewise, similar results have been shown in human osteosarcoma cells (51) and laryngeal and hypopharyngeal squamous cell carcinoma metastases (52, 53). Classically, the ERK1/2 signaling cascade is not a target of PTEN; however, Thomas et al. reported that PTEN reconstitution in SPARC (secreted protein acidic and rich in cysteine) suppressed the SHC/RAF/ERK signaling pathway in SPARC-expressing cells (54). Moreover, restoration of wild-type PTEN induced apoptosis in Jun(+/−) cells undergoing cellular transformation by oncogenic Ras (55).

In summary, metastatic signature genes (e.g., chemokine and growth factor receptor/ligand axes) have been implicated to facilitate the cell autonomous transforming functions of a primary disease to a malignant disease throughout the course of tumor progression. Because loss of PTEN activity in advanced, metastatic prostate cancers leads to increased cell proliferation, reduced cell death, and metastasis, it is not implausible to suggest that loss of PTEN activity in prostate cancer provides the permissive switch to a CXCR4-mediated advanced, metastatic disease. Current management options for prostate cancer are hormonal therapy for early-stage tumors and chemotherapy, which is often reserved for diseases that have spread beyond the prostate. Radiation therapy may be used for some advanced tumors. Overall, the treatment options for advanced, metastatic prostate cancers become slim, often relying on general chemotherapy and radiation. During advanced stages of prostate cancer, these treatment options are geared toward easing symptoms rather than slowing the disease. Deregulated CXCR4, PI3K/AKT, and/or MAPK signaling pathways substantially contribute to the pathogenesis of prostate cancers. Likewise, PTEN inactivation is associated with a hormone-refractory disease (22). Understanding the relationship between PTEN and CXCR4 will lead to new treatment options, especially for aggressive, androgen-insensitive cancers that express low or diminished levels of PTEN and high levels of CXCR4. Thus, when hormone therapy is no longer an option, antagonists against CXCR4, PI3K/AKT, and/or MAPK signaling could prove to be beneficial in regulating tumor progression once PTEN expression and function is lost. We suggest that targeted therapies against these critical and frequent events (loss of PTEN, upregulation of CXCR4 expression in advanced prostate cancers) should be tested in the future in combination with current chemotherapeutic agents.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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References

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