Plk1 inhibition enhances the efficacy of androgen signaling blockade in castration-resistant prostate cancer

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Running title: Plk1 in CRPC

Keywords: Oxidative stress, androgen receptor, the PI3K/AKT/mTOR pathway, castration-resistant prostate cancer, Plk1

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Disclosure of Potential Conflicts of Interest: No potential conflicts of interest are disclosed by the authors
Abstract

Prostate cancer (PCa) is thought to be driven by oxidative stress, lipid metabolism, androgen receptor (AR) signaling and activation of the PI3K/AKT/mTOR pathway, but it is uncertain how they may become coordinated during progression to castration-resistant disease which remains incurable. The mitotic kinase polo-like kinase 1 (Plk1) is elevated in PCa where its expression is linked to tumor grade. Notably, Plk1 signaling and lipid metabolism were identified recently as two of the top five most upregulated pathways in a mouse xenograft model of human PCa. Herein, we show that oxidative stress activates both the PI3K/AKT/mTOR pathway and AR signaling in a Plk1-dependent manner in prostate cells. Inhibition of the PI3K/AKT/mTOR pathway prevented oxidative stress-induced activation of AR signaling. Plk1 modulation also affected cholesterol ester accumulation in PCa via the SREBP pathway. Lastly, Plk1 inhibition enhanced cellular responses to androgen signaling inhibitors (ASI) and overcame ASI resistance in both cultured PCa cells and patient-derived tumor xenografts. Given that activation of AR signaling and the PI3K/AKT/mTOR pathway is sufficient to elevate SREBP-dependent expression of key lipid biosynthesis enzymes in castration-resistant PCa, our findings argued that Plk1 activation was responsible for coordinating and driving these processes to promote and sustain the development of this advanced stage of disease. Overall, our results offer a strong mechanistic rationale to evaluate Plk1 inhibitors in combination drug trials to enhance the efficacy of androgen signaling inhibitors in castration-resistant prostate cancer.
Introduction

Prostate cancer (PCa) is the second leading cause of death due to cancer in males in the United States, with 233,000 news cases and 29,480 deaths estimated in 2014 (1). Treatment options for late stage disease are limited. Androgen-deprivation therapy is initially effective, but remissions are temporary and the disease eventually progresses to castration-resistant prostate cancer (CRPC). Evidence from experimental and clinical studies suggests that PCa cells are exposed to increased oxidative stress. A potential role for reactive oxygen species (ROS) in the regulation of cellular processes controlling malignant transformation holds a lot of promise in understanding PCa, as this will open doors for the development of novel therapeutics for the disease (2). Besides acting as a DNA-damaging agent, moderately elevated levels of ROS may act as secondary messengers that contribute to the oncogenic phenotype by activating many transcription factors and signaling pathways. Therefore, identification of prostate-specific signaling pathways in response to oxidative stress will provide novel targets for treatment options (2).

The androgen receptor (AR) is a critical effector of PCa development and progression. In response to androgen, activated AR is translocated from the cytoplasm into the nucleus, acting as a transcription factor that activates many downstream proteins, such as prostate specific antigen (PSA). Enough evidence suggests that AR signaling continues to be essential for PCa development even after castration. In support, current approaches to treat CRPC are to delay or replace treatment with cytotoxic agents such as docetaxel with Androgen Signaling Inhibitors (ASI), such as abiraterone and enzalutamide (previously MDV3100) (3,4). However, overall survival was only improved by five or two months in the recent phase III trials that compared abiraterone or enzalutamide with placebo in CRPC patients (4-6). Therefore, new mechanism-based studies are urgently needed to identify targets and strategies to overcome ASI resistance, thus achieving effective management of CRPC.

It has been established that the PI3K/AKT/mTOR pathway plays a critical role in PCa cell survival. The
PI3Ks are enzymes that are responsible for generation of the second messenger phosphatidylinositol 3,4,5-triphosphate (PIP3) that activates AKT, which mediates activation of the mTOR complex, a kinase that controls protein translation via activation of S6K and S6. The tumor suppressor PTEN (phosphatase and tensin homolog) acts as a major antagonist to the PI3K pathway. Although prostate-specific knockout of PTEN leads to invasive PCa and ultimately to metastatic cancer in mice (7), loss-of-function PTEN mutations are detected in less than 5% of primary prostate tumors, suggesting that additional mechanisms might be responsible for activation of the PI3K/AKT/mTOR pathway in PCa.

Increasing evidence in recent years suggests that deregulation of lipid metabolism is another hallmark of PCa. For example, high contents of both free cholesterol and cholesteryl esters (CE) of prostate tissues correlate with the presence of malignancy, likely due to abnormalities in lipid homeostasis (8). Key players in the regulation of lipid metabolism are the sterol regulatory element binding proteins (SREBPs), a family of three transcription factors (SREBP-1a, SREBP-1c, SREBP-2) that are attached to the endoplasmic reticulum as inactive forms. When sterol levels are low, SREBPs will be activated by SREBP-cleavage-activating protein (SCAP) to drive expression of enzymes needed for lipid synthesis, such as FAS (fatty acid synthase), HMGCoA-R and LDL-R (9). Of note, both the PI3K/AKT/mTOR and AR pathways act upstream of the SREBP pathway, resulting in elevation of lipid synthesis (Fig. 7) (10,11). Cholesterol can serve as a precursor to drive de novo steroidogenesis to increase intratumoral androgen levels, thus activating AR signaling (12). Cholesterol, combined with increased levels of fatty acid, will also increase the formation of lipid rafts, which have documented roles in activation of the PI3K/AKT/mTOR pathway and cell migration (Fig. 7). Despite all these progresses, whether and how oxidative stress and various signaling pathways are coordinated to contribute to CRPC is not known.

Polo-like kinase 1 (Plk1) is a regulator of many cell cycle events, such as mitotic entry and cytokinesis (13). A close correlation between the level of Plk1 expression and prognosis has been documented.
Therefore, it has been proposed that inhibition of Plk1 is an important strategy for enhancement of cancer therapy (13). Indeed, the Plk1 inhibitor BI2536 is in phase II clinical studies for patients with various cancers. Significantly, Plk1 is overexpressed in PCa and is linked to higher grade tumors, suggesting that Plk1 is involved in tumorigenesis and progression in this tumor entity (14). Furthermore, RNAi-mediated Plk1 knockdown causes induction of mitotic catastrophe in PCa cells, suggesting that Plk1 might be a target for PCa management (14). Of note, Plk1 and lipid metabolism are two of the top five most-upregulated pathways after castration in a microarray analysis of a PCa xenograft model (15). However, the molecular mechanisms responsible for these encouraging observations are still undefined. Our data explains how castration-associated Plk1 elevation induces activation of the PI3K/AKT/mTOR and AR pathways and increase of lipid biosynthesis, eventually resulting in CRPC. Our finding supports the notion that inhibition of Plk1 is a novel avenue to enhance the efficacy of ASI in CRPC.

Materials and Methods

Cell culture

RWPE-1 cells were cultured in Keratinocyte Serum Free Medium (K-SFM) (Invitrogen, 17005-042) supplemented with 50 μg/ml Bovine Pituitary Extract (BPE), 5 ng/ml epidermal growth factor (EGF, Human Recombinant), 100 units/ml penicillin, and 100 units/ml streptomycin at 37°C in 8% CO2. HEK293T and DU145 cells were cultured in Dulbecco Modified Eagle medium (DMEM) supplemented with 10% (vol/vol) fetal bovine serum (FBS), 100 units/ml penicillin and 100 units/ml streptomycin at 37°C in 8% CO2. PC3 cells were cultured in F12K supplemented with 10% (vol/vol) fetal bovine serum (FBS), 100 units/ml penicillin, and 100 units/ml streptomycin at 37°C in 8% CO2. LNCaP, C4-2, 22Rv1 and MR49F cells were cultured in RPMI-1640 (ATCC) supplemented with 10% FBS (vol/vol), 100 units/ml penicillin, and 100 units/ml streptomycin at 37°C in 8% CO2. For MR49F cells, 10 μmol/l MDV3100 was added to the medium to maintain the MDV3100 resistance.
siRNAs targeting AR splice variants in 22Rv-1 cells were synthesized by Thermo Scientific Dharmacon. The targeting sequences are AAUCUUGAGGGUGUUUGGAGUUU for AR-V1 and AAUGACCAGACCCUGAAGAAUUU for AR-V7. Control siRNA was ordered from Santa Cruz (sc-37007). Lipofectamine 2000 Reagent (Invitrogen, 11668-019) was used for DNA or siRNA transfection.

**Drugs**

Pyrrolidine dithiocarbamate (PDTC), diamide, dihydrotestosterone (DHT), R1881, insulin, LY294002 and nocodazole were purchased from Sigma. Diphenyleneiodonium chloride (DPI) and BI2536 were purchased from Calbiochem, Symansis respectively. Abiraterone, MDV3100 (enzalutamide), MK2206 and rapamycin were purchased from Selleckchem.

**Western blotting**

Harvested cells were lysed in TBSN buffer (20 mM Tris, pH 8.0, 150 mM NaCl, 1.5 mM EDTA, 5 mM EGTA, 0.5% Nonidet P-40, and 0.5 mM Na$_3$VO$_4$) supplemented with proteinase inhibitors. The lysates were resolved by SDS-PAGE and transferred to Whatman Westran PVDF membrane (Sigma, Z671088), followed by incubation with antibodies against Plk1 (Santa Cruz, sc-17783), phospho-AKT-S473 (Cell Signaling, 9271), phospho-AKT-T308 (Cell Signaling, 13038), AKT (Cell Signaling, 9272), phospho-S6K (Cell Signaling, 9205), phospho-S6 (Cell Signaling, 2211), S6 (Cell Signaling, 2217), phospho-NFκB (Cell Signaling, 3033), NFκB (Santa Cruz, sc-372), AR (Santa Cruz, sc-7305), γ-tubulin (Sigma, T3559), p84 (Abcam, ab487), Twist1 (Sigma, SAB1411370), SREBP1 (Santa Cruz, sc-367), SREBP2 (Santa Cruz, sc-5603), phospho-GSK3β (Cell Signaling, 9322), GSK3β (BD Biosciences, 610201), FAS (BD Biosciences, 610962), HMG-CoA Reductase (EMD Millipore, ABS229), cleaved-PARP (EMD Millipore, AB3620), PSA (Cell Signaling, 5365), and β-actin (Sigma, A5441).

**Cytoplasmic and nuclear protein extract preparations**
Cytoplasmic and nuclear protein extracts were prepared with a kit from ActiveMotif (Cat No. 40410) according to the manufacturer’s instructions.

**Immunofluorescent staining**

Cells were fixed with 4% paraformaldehyde for 10 minutes, washed with 0.1% Triton X-100 PBS, and permeabilized with methanol for 2 minutes. Upon wash with 0.1% Triton X-100 PBS, cells were blocked with 3% bovine serum albumin in PBS for 10 minutes and incubated with anti-AR antibody for 2 hours at room temperature, followed by incubation with Alexa Fluor® 555 Goat Anti-Mouse IgG (H+L) secondary antibody (Invitrogen, A21424) and 4,6-diamidino-2-phenylindole (DAPI, Sigma) for 1 hour.

**Depletion and overexpression of Plk1**

HEK293T cells in 10-cm dishes were co-transfected with 4 µg of pHR'-CMV-ΔR 8.20vpr, 2 µg of pHR'-CMV-VSV-G, and 4 µg of pLKO.1-Plk1 for depletion of Plk1 or LV-CMV-Plk1 for overexpression of Plk1. Supernatants were collected every 12 hours after 24 hours post-transfection. Viruses were filtered through a 0.45-µm poresize filter, concentrated by spin at 20,000 rpm for 2 hours, re-suspended in TNE buffer (50 mM Tris-HCl, pH 7.8, 130 mM NaCl, 1 mM EDTA), and rotated overnight at 4°C. Infections were carried out in the presence of 10 µg/ml of polybrene and 10 mM of HEPES, followed by selection with 1 µg/ml of puromycin for at least 36 hours.

**Cholesterol ester (CE) measurement by Raman spectrometry**

CE measurement by Raman spectrometry was performed with a compound Raman microscope as described previously (8).

**Patient-derived xenograft model**

Mice carrying LuCaP35CR tumors were obtained from Dr. Robert Vessella at University of Washington (16). Tumors were amplified by cutting the original tumors into about 20–30 mm³ pieces and then implanted into pre-castrated nude mice. After amplifying enough tumors, tumors were harvested and cut into about
20–30 mm³ pieces before implanting into 16 pre-castrated nude mice. When tumors reached 250 to 300 mm³, mice were randomly separated into 4 groups (4 mice in each group) for different treatments. Tumor volume was calculated as Length x Width²/2. BI2536 was dissolved in 0.1M HCl and then diluted in 0.9% NaCl for injection. Blood was collected once a week and serum PSA level was measured using the PSA ELISA kit (Abnova, KA0208).

Results

Plk1 acts upstream of the PI3K/AKT/mTOR pathway during oxidative stress

In order to understand how Plk1 is involved in CRPC, we treated prostate cells with oxidative stress, as castration induces oxidative stress in vivo, and treatment with H₂O₂ can partially mimic cellular events after castration. Genetic backgrounds of different prostate cell lines we used in this study are indicated in Fig. 1A. Treatment of two PCa cell lines, PC3 and DU145, with hydrogen peroxide led to increased levels of Plk1 (Fig. 1B). In agreement, inhibition of oxidative stress with DPI reduced the levels of Plk1 in multiple prostate cell lines, including RWPE-1, a non-transformed prostate cell line that is established by transfection with a single copy of the human papilloma virus 18 into epithelial cells derived from the peripheral zone of a histologically normal adult human prostate (Fig. 1C). Considering that the PI3K/AKT/mTOR pathway has an established role in PCa, we next asked whether oxidative stress results in activation of this pathway as well. As indicated in Fig. 1D-F, treatment of cells with hydrogen peroxide led to phosphorylation of AKT in multiple prostate cell lines, including RWPE-1. We also asked whether oxidative stress other than hydrogen peroxide can cause activation of the PI3K/AKT/mTOR pathway as well. Diamide oxidizes cellular thiols, especially protein-integrated cysteines, provoking a rapid decrease in cellular glutathione, hence causing oxidative stress. Diamide treatment also activated the PI3K/AKT/mTOR pathway in PC3 cells (Fig. 1G).

Having established that oxidative stress leads to elevation of Plk1 and activation of the PI3K/AKT/mTOR pathway, we next asked whether these two events are interrelated and interdependent.
Towards that end, we used lentivirus-based RNAi to deplete Plk1 in different prostate cell lines, and found that depletion of Plk1 caused a reduction of the levels of phospho-AKT (S473) and phospho-S6, either in the absence or presence of oxidative stress, suggesting that Plk1 acts upstream of the PI3K/AKT/mTOR pathway (Fig. 1H, 1I). As a control, we showed that the short treatment with H2O2 did not affect cell cycle progression, ruling out the possibility oxidative stress-induced elevation of Plk1 might be a secondary effect of cell cycle arrest (Fig. 1I, right panel). To further confirm that oxidative stress-induced activation of AKT is Plk1 dependent, we also inhibited the PI3K/AKT/mTOR pathway with various inhibitors, and found that these inhibitors did not affect oxidative stress-induced elevation of Plk1, supporting that the PI3K/AKT/mTOR pathway acts downstream of Plk1 (Fig. 1J). Mechanistically, oxidative stress-induced Plk1 elevation and activation of the PI3K pathway are NF-κB dependent, as addition of PDTC, an NF-κB inhibitor, counteracted the effect (Fig. 1K-1M). In agreement with that NF-κB is a transcription factor, oxidative stress also results in an elevation of mRNA level of Plk1 (Fig. 1K). Involvement of NF-κB is also supported by its increased phosphorylation upon oxidative stress (Fig. 1L). As a control, we showed that the nuclear localization of NF-κB was increased upon oxidative stress (Fig. 1N). NF-κB, a transcription factor that regulates a spectrum of biological responses, is activated by a variety of stimuli, such as radiation and oxidative stress (17). Certain cell types, but certainly not all, respond to oxidative stress by up-regulation of NF-κB activity. Our data suggest that NF-κB plays a critical role in prostate cells in response to oxidative stress (Fig. 1K-1M). How NF-κB affects Plk1 expression has been described (18). Plk1 is a transcriptional target of the RelA subunit of NF-κB and upregulation of Plk1 induced by cell detachment is RelA dependent (18). Our finding suggests that NF-κB might be responsible for elevation of Plk1 in CRPC in which the constitutive activation of NF-κB is observed (19).

**Oxidative stress induces activation of AR signaling in a Plk1-dependent manner**

In addition to the PI3K/AKT/mTOR pathway, continued activation of AR signaling contributes to CRPC.
We therefore asked whether oxidative stress leads to activation of AR signaling in vitro. Treatment of LNCaP cells with hydrogen peroxide resulted in elevation of both AR protein and mRNA (Fig. 2A), whereas inhibition of oxidative stress with DPI led to decreased levels of AR in multiple PCa cell lines, including two CRPC cell lines, C4-2 and 22Rv1 (Fig. 2B), suggesting that oxidative stress is likely one contributing factor that activates AR signaling in CRPC. We then asked whether oxidative stress-associated AR activation is Plk1 dependent with different approaches. Lentivirus-mediated overexpression of Plk1 increased the expression levels of AR in LNCaP cells either in the presence or absence of DPI (Fig. 2C). Plk1 overexpression led to an increase of AR protein in C4-2 cells as well (Fig. 2D). In agreement, BI2536-mediated inhibition of Plk1 decreased the expression levels of AR in LNCaP cells either in presence or absence of oxidative stress (Fig. 2E, 2F). We also noticed that AR level of C4-2 cells was much more sensitive to BI2536 than that of LNCaP cells, indicating that Plk1 likely plays a more important role in late stage PCa (Fig. 2G). Considering that AR is a transcription factor, which has to shuttle into the nucleus to control its downstream targets, we also analyzed its subcellular localization by fractionation upon inhibition of Plk1. As indicated, inhibition of Plk1 by BI2536 led to reduced levels of nuclear AR either in the absence (Fig. 2H) or presence of oxidative stress (Fig. 2I). The reduced levels of nuclear AR upon inhibition of Plk1 under different cellular conditions, such as oxidative stress and DHT treatment, were also confirmed by anti-AR immunofluorescent (IF) staining (Fig. 2J). Furthermore, treatment of LNCaP cells with BI2536 inhibited AR transactivation activity in a dose-dependent manner in the AR luciferase assay (Fig. 2K). Because oxidative stress activates both the PI3K/AKT/mTOR pathway and AR signaling, we asked whether these two pathways regulate each other under this condition. As indicated in Fig. 2L, 2M, treatment of LNCaP and C4-2 cells with various inhibitors of the PI3K/AKT/mTOR pathway significantly antagonized oxidative stress-induced AR activation. Therefore, the PI3K/AKT/mTOR pathway also contributes to AR activation upon oxidative stress. To understand the underlying mechanism of this observation, we turned our
attention to Twist1 transcription factor. It was shown that AKT phosphorylation of Twist1 at S42 leads to its activation to promote cell survival during carcinogenesis (20), and that activated Twist1 increases AR expression through binding to E-boxes in AR promoter region upon castration-induced oxidative stress (21). Because Twist1 is an important mediator between AKT and AR, we asked whether inhibition of Plk1 affects the nuclear accumulation of Twist1. As indicated, treatment of C4-2 cells with both BI2536 and MK2206 led to an obvious reduction of nuclear Twist1 protein level (Fig. 2N). Of interest, the cytosolic fraction of Twist1 was apparently increased upon treatment with BI2536 and MK2206 (Fig. 2N), suggesting that it is the nuclear localization of Twist1 is regulated by Plk1 and AKT. Finally, BI2536 treatment clearly inhibited insulin-induced transcription of CLU and AR, two Twist1 targets (Fig. 2O), in agreement with a reduced protein level of nuclear Twist1 (Fig. 2N).

**Plk1 affects cholesterol metabolism in PCa cells via the SREBP pathway**

To confirm that Plk1 regulates AR signaling, we then analyzed the status of the SREBP pathway upon inhibition of Plk1 with BI2536. Treatment of LNCaP and C4-2 cells with BI2536 led to reduced levels of cleaved forms of SREBP2 (Fig. 3A) and SREBP1 (Fig. 3B). To ask whether this observation is limited to AR-positive cells, we also performed a series of Western blotting analyses with antibodies against SREBP1/2 in PC3 and DU145 cells. Inhibition of Plk1 with BI2536 also reduced the expression levels of cleaved forms of SREBP2 (Fig. 3C) and SREBP1 (Fig. 3D) in PC3 and DU145 cells, suggesting that BI2536-induced downregulation of SREBP pathway is likely a general phenomenon in PCa. To further confirm this, we tested whether inhibition of Plk1 affects the downstream targets of SREBP. As indicated in Fig. 3E, BI2536 treatment led to reduced transcription levels of FAS, MVK and HMGCR, three targets of SREBP, supported by decreased levels of proteins upon BI2536 treatment (Fig. 3F). Of note, 4 hours treatment with BI2536 is enough for us to detect significant reductions of these genes in C4-2 cells, whereas 24 hour is needed to observe an apparent inhibition in LNCaP cells (Fig. 3E), suggesting that
androgen-independent C4-2 cells are much more sensitive to BI2536 than androgen-dependent LNCaP cells. Considering that SREBP is also regulated by the Fbw7/GSK3β pathway and that AKT-associated phosphorylation suppresses GSK3β, we thus tested whether BI2536 also affects the activation of GSK3β. As indicated in Fig. 3G, inhibition of Plk1 also reduced phosphorylation level of GSK3β, suggesting that the AKT/GSK3β axis might be also involved in Plk1-dependent activation of the SREBP pathway. Furthermore, to answer the question whether a general decay of cellular protein is the cause for reduced AR and FAS levels following BI2536 treatment, we performed a time course experiment in which an apoptosis analysis was included. BI2536 treatment led to reduced levels of AR and FAS after 8h incubation, but cell death was not detected until 12h, ruling out the possibility that Plk1 inhibition-induced reduction of AR and FAS levels in LNCaP cells is a secondary effect of cell death (Fig. 3H). For C4-2 cells, as short as 4h of BI2536 treatment is enough for us to detect apparent reduction of AR and FAS levels.

Using a stimulated Raman scattering microscope, we recently reported that the high-grade PCa tissues contained significantly more cholesterol ester (CE) than the low-grade ones, suggesting an important correlation of CE accumulation with PCa progression (8). Of significance, inhibition of Plk1 reduced the level of CE in PC3 cells in a concentration-dependent manner (Fig. 3I), suggesting that Plk1 acts upstream of cholesterol synthesis during PCa progression. In support, lentivirus-mediated overexpression of Plk1 increased CE accumulation in PC3 cells (Fig. 3J), confirming that Plk1 acts upstream of cholesterol biosynthesis in PCa progression. We next asked whether oxidative stress affects CE accumulation in PCa. As expected, diamide treatment increased the level of CE in PC3 cells (Fig. 3K, 3L). Because Plk1-associated kinase activity affects cholesterol metabolism and because cholesterol is the precursor of androgen during de novo steroidogenesis, we asked whether there is a positive feedback loop between AR signaling and cholesterol biosynthesis (Fig. 7). In other words, Plk1-mediated activation of AR signaling increases cholesterol biosynthesis via the SREBP pathway, and elevation of cholesterol levels further activates AR
signaling via de novo androgen biosynthesis. As indicated, treatment with abiraterone, an inhibitor of androgen biosynthesis, prevented oxidative stress-induced activation of AR signaling, suggesting a positive feedback loop (Fig. 3M). For the similar reason, we also asked whether there is another positive feedback loop between the PI3K/AKT/mTOR pathway and lipid synthesis (Fig. 7). In other words, Plk1-mediated activation of the PI3K/AKT/mTOR pathway increases lipid synthesis via the SREBP pathway, and elevation of fatty acid and cholesterol levels further activates the PI3K/AKT/mTOR pathway in lipid rafts. As indicated, treatment with the lipid raft-disrupting agent, filipin, a polyene macrolide that binds cholesterol with high specificity, reduced oxidative stress-induced activation of AKT, supporting a positive feedback loop as well (Fig. 3N, 3O).

**AR positively regulates Plk1**

Given that AR is a transfection factor, we also asked whether AR regulates the level of Plk1. As indicated, AR expression in PC3 and 293T cells led to elevation of Plk1 transcription (Fig. 4A) and AR depletion in LNCaP and C4-2 cells resulted in reduction of Plk1 protein (Fig. 4B). We acknowledge that recent evidence suggests that AR splice variants (AR-vs) that lack the functional ligand-binding domain (LBD) also play important roles in resistance to ASI in CRPC (22-24). AR-vs originate from AR transcripts with insertions of cryptic exons downstream of the coding sequences for AR DNA-binding domain (e.g., AR-v7) or with deletions of exons coding for AR-LBD (e.g., AR-v567es). Microarray data show that AR-WT and AR-vs mediate distinctive transcriptional programs, as AR-vs preferentially induce elevation of cell-cycle genes, including Plk1 (22). Thus, we asked whether depletion of AR-vs affects the level of Plk1. As indicated, depletion of both AR-V7 and AR-V1 caused obvious reduction of the levels of Plk1 protein (Fig. 4C, top panel) and mRNA (Fig. 4C, bottom panel).

**Inhibition of Plk1 potentiates the effect of ASI**

Because Plk1 elevation leads to constitutive activation of AR, the major mechanism for development of
resistance of ASI, we performed a series of experiments to ask whether ASI and BI2536 inhibit AR signaling in CRPC cells in a synergistic manner. A combination of low concentrations of abiraterone and BI2536 resulted in a much more dramatic reduction of protein levels of AR-WT in C4-2 (Fig. 4D) and AR-vs in 22Rv1 cells (Fig. 4E). Moreover, a combination of low concentrations of enzalutamide (MDV3100) and BI2536 also led to a more significant reduction of AR-WT in C4-2 (Fig. 4F) and AR-vs in 22Rv1 cells (Fig. 4G). Of note, elevation of AR-vs has been reported to contribute to resistance to inhibition of AR signaling in CRPC (23,24). Thus, the data in Fig. 4E, 4G suggest that a combination of BI2536 and ASI could be a novel avenue to overcome ASI-resistance due to elevation of AR-vs. Next, we performed FACS (fluorescence-activated cell sorting) analysis to follow any cell cycle defect upon drug treatment. As indicated, presence of enzalutamide potentiated BI2536-induced G2/M arrest in 22Rv1 cells (Fig. 4H). Furthermore, a combination of BI2536 and enzalutamide strongly antagonized R1881-induced nuclear accumulation of AR in LNCaP cells (Fig. 4I). We also asked whether BI2536 and enzalutamide act synergistically in LNCaP cells by measuring the combination index with the following equation: c.i. = (Am)50/(As)50 + (Bm)50/(Bs)50, where (Am)50 is the IC50 of drug A in the combination, (As)50 is the concentration of drug A that will produce the identical level of effect alone, (Bm)50 is the IC50 of drug B in the combination and (Bs)50 is the IC50 of drug B after single administration. Antagonism is indicated when c.i.>1, c.i.=1 indicates an additive effect and c.i.<1 indicates synergy. Our calculations led to a c.i. value of 0.12, suggesting that BI2536 and enzalutamide act synergistically to induce apoptosis (Fig. 4J). Finally, androgen treatment of LNCaP cells growing in CSS medium apparently stimulated Plk1 expression, and enzalutamide treatment of LNCaP cells culturing in normal medium inhibited the expression level of Plk1, further confirming that Plk1 is an AR target (Fig. 4K).

**Inhibition of Plk1 overcomes ASI resistance**

Next, we treated MR49F cells, the enzalutamide-resistant LNCaP cells (25), with enzalutamide and
BI2536 and found that MR49F cells became much more sensitive to enzalutamide in the presence of BI2536, indicated by an almost complete disappearance of AR protein and a huge increase of c-PARP (Fig. 5A, 5B). Furthermore, treatment with BI2536 plus enzalutamide led to a much stronger G2/M arrest and androgen-induced AR nuclear localization than monotherapy in MR49F cells (Fig. 5C, 5D). Finally, the castration-resistant LuCaP35CR xenograft tumors, directly derived from human patients with CRPC (24), were used to test the efficacy of the combination of BI2536 and abiraterone. As indicated, the combination of BI2536 and abiraterone almost completely blocked tumor growth and elevation of serum PSA. In striking contrast, monotherapies with low concentrations of BI2536 or abiraterone did not significantly affect tumor growth and serum PSA levels (Fig. 6A-D). To support our cell culture-based data, the levels of testosterone, the precursor of DHT, were reduced in both BI2536 and abiraterone-treated tumors. A combination of BI2536 and abiraterone led to the most significant inhibition of the level of testosterone (Fig. 6E). Consistent with these mass spectrometry-based measurements, lipid droplets in the LuCaP35CR tumors were dramatically reduced upon BI2536 treatment (Fig. 6F). Of note, we recently reported that the major component of lipid droplets in PCa was found to be cholesterol ester (26).

**Discussion**

**Oxidative stress in PCa**

Evidence from both experimental and clinical studies suggests that PCa cells are exposed to increased oxidative stress (2,27). Indeed, it has been demonstrated that oxidative stress is inherent in prostate cancer cells (28). Therefore, understanding how reactive oxygen species (ROS) regulate cellular processes controlling transformation during the progression of PCa will open doors for the development of novel therapeutics for PCa (2). In particular, castration, the major approach for treatment of late stage PCa (29), significantly increases oxidative stress of the prostate (21,27,30). However, whether and how castration-induced oxidative stress contributes to CRPC is still elusive. Herein, we provide evidence to show
that oxidative stress led to activation of the PI3K/AKT/mTOR pathway (Fig. 1), activation of AR signaling (Fig. 2), and elevation of cholesterol biosynthesis (Fig. 3), three hallmarks of CRPC. Of note, Plk1 turns out to be a critical molecule that links all these PCa-specific signaling pathways. We understand that 1 mM H₂O₂ treatment might not be physiological relevance. We initially chose such treatment, as used previously (31), to establish a link among oxidative stress, Plk1 and signaling pathways that are involved in PCa. Additional experiments without H₂O₂ treatment further confirmed that Plk1-associated kinase activity activates these pathways is a general phenomenon.

**ASI in CRPC treatment**

CRPC remains an incurable disease today. AR antagonists such as bicalutamide and nilutamide have been used in CRPC for 3 decades. Unfortunately, the duration of response to these anti-androgens is often less than 4 months; their AR binding is reversible, and paradoxical agonism of the AR occurs in 10 to 15% of patients (32). Two most recently FDA-approved drugs to treat CRPC are abiraterone and enzalutamide, which improve overall survival for 5 months and 2 months, respectively (4,5). While abiraterone acetate blocks de novo androgen biosynthesis from cholesterol, enzalutamide is a direct AR inhibitor. Based on mutual regulation of Plk1 and AR, we hypothesized that inhibition of Plk1 might be a novel approach to overcome resistance to ASI (Fig. 7). Both cell culture-based in vitro assays and patient-derived xenograft tumor experiments led to the conclusion that inhibition of Plk1 significantly enhanced the efficacy of ASI in CRPC. Because BI2536 has been well tolerated by patients in clinical trials, and because we used much lower concentrations of BI2536 and ASI than the previous publications, the data presented here support an immediate clinical trial with a combination of BI2536 and ASI to improve the treatment of CRPC.

**Plk1 in drug resistance**

Increasing evidence suggests that Plk1 has many non-mitotic functions. In particular, Plk1 is significantly elevated in interphase of transformed cells, but not in normal cells, suggesting that Plk1 must...
have cancer cell specific functions (33). In support, elevation of Plk1 leads to inactivation of tumor suppressor p53 via its kinase activity towards GTSE1 and Topors, two negative regulators of p53 (34,35). Because many chemotherapeutic drugs such as doxorubicin act via p53-dependent cell cycle arrest and apoptosis, Plk1 elevation has been proposed to contribute to development of chemoresistance. Plk1 phosphorylation of CLIP-170 and p150Glued, two microtubule plus-end binding proteins, led to increased microtubule dynamics, thus reducing the efficacy of taxol, an inhibitor of tubulin depolymerization (36-38). We also showed that Plk1 phosphorylation of Orc2 and Hbo1, two members of DNA replication machinery, increased DNA replication in the presence of replication stress, eventually contributing to development of resistance to additional chemotherapeutic drugs that cause DNA replication stress such as gemcitabine (39-41). The data presented here demonstrated that Plk1 also plays a critical role in cellular response to ASI and that inhibition of Plk1 overcomes ASI resistance in CRPC. While how Plk1 elevation leads to activation of AR signaling and elevation of cholesterol biosynthesis are currently under heavy investigation in the Liu lab, we recently reported one mechanism that is responsible for Plk1-dependent activation of the PI3K/AKT/mTOR pathway. We showed that Plk1 phosphorylation of PTEN-S385 leads to its inactivation, thus activation of the PI3K/AKT/mTOR pathway (42).

Acknowledgement

We appreciate Dr. Amina Zoubeidi for MR49F cells and Dr. Robert Vessella for LuCaP35CR mouse line. This work was supported by NIH grant R01 CA157429 (X.L.), NIH grant R01 AR059130 (N.A.), NSF grant MCB-1049693 (X.L.) and ACS grant RSG-13-073 (X.L.). Zhe Zhang, Xianzeng Hou and Chen Shao were financially supported by China Scholarship Council (CSC). Xenograft data were acquired by a Purdue Center for Cancer Research facility supported by P30 CA023168 and support for this publication made possible by P30 CA023168.
Figure legends

Figure 1. Oxidative stress activates the PI3K/AKT/mTOR pathway in a Plk1-dependent manner in prostate cells. A, genetic backgrounds of prostate cells used in the study. B, moderate oxidative stress leads to increased levels of Plk1 in PCa cells. PC3 and DU145 cells were treated with or without 1 mM of H2O2 for 5 minutes and harvested for anti-Plk1 immunoblotting (IB). C, inhibition of oxidative stress leads to reduced levels of Plk1 protein. RWPE-1, LNCaP, DU145 and PC3 cells were treated with or without 20 µM of DPI (diphenyleneiodonium), an inhibitor of NADPH oxidase, in the presence of 200 ng/ml of nocodazole for 10 hours and harvested. D and E, oxidative stress activates the PI3K/AKT/mTOR pathway in RWPE-1 cells. RWPE-1 cells were treated with different concentrations of H2O2 for 10 minutes (the left four lanes in D) or with 1 mM of H2O2 for different times (the right four lanes in D and E) as indicated and harvested for anti-p-AKT IB. F, oxidative stress activates the PI3K/AKT/mTOR pathway in multiple prostate cell lines. RWPE-1, LNCaP, DU145 and PC3 cells were treated with 1 mM of H2O2 for 5 minutes and harvested. G, PC3 cells were treated with diamide for various conditions as indicated. H and I, oxidative stress-induced activation of the PI3K/AKT/mTOR pathway is Plk1 dependent. RWPE-1 (H) or PC3 (I) cells were depleted of Plk1 by infection with lentivirus. After selection for infection-positive cells with puromycin for 36 hours, cells were treated with 1 mM of H2O2 for 5 minutes and harvested for IB or FACS. In the right panel of (I), cells were treated with or without nocodazole (Noc.) for 12h before treatment with H2O2. J, inhibition of the PI3K/AKT/mTOR pathway did not affect oxidative stress-induced elevation of Plk1 protein. PC3 cells were pre-incubated with two inhibitors of the PI3K/AKT/mTOR pathways (25 µM of LY294002 for 1 hour or 100 nM of rapamycin for 2 hours), treated with 1 mM H2O2 for 5 minutes, and harvested for IB. K and L, oxidative stress-induced elevation of Plk1 is NF-κB dependent. PC3 or LNCaP cells were incubated with 100 µM of PDTC for 10 minutes, treated with or without 1 mM of H2O2 for 5 minutes, and harvested for RT-PCR to measure Plk1 mRNA levels (K) or IB with antibodies indicated (L). M, oxidative stress-induced
activation of the PI3K/AKT/mTOR pathway is NF-κB dependent. LNCaP cells were incubated with 100 µM of PDTC for 30 minutes, treated with 1 mM of H₂O₂ for 5 minutes, and harvested for IB. N, Oxidative stress increased nuclear accumulation of NF-κB. LNCaP cells were treated with 1 mM of H₂O₂ for 5 minutes, and harvested for immunofluorescence (IF) staining against NF-κB.

**Figure 2.** Oxidative stress-induced AR elevation in PCa cells is Plk1 dependent. A, oxidative stress results in elevation of AR level. LNCaP cells were treated with or without 1 mM of H₂O₂ for 5 minutes and harvested for anti-AR IB or RT-PCR. B, inhibition of oxidative stress reduces AR levels in PCa cells. LNCaP, C4-2 and 22Rv-1 cells were treated with 20 µM of DPI for 24 hours and harvested. C and D, overexpression of Plk1 increases the level of AR protein. C, LNCaP cells were infected with lentivirus that expresses Plk1 for 24 hours, treated with 20 µM DPI for 12 hours, and harvested. D, C4-2 cells were infected with lentivirus to deplete or overexpress Plk1 for 24 hours and harvested. E and F, inhibition of Plk1 prevents oxidative stress-induced elevation of AR protein. LNCaP cells were pre-incubated with or without 100 nM of BI2536 for 2 hours, treated with 1 mM of H₂O₂ for 5 minutes (E) or 1 mM of diamide for 5 minutes (F), and harvested. G, AR of C4-2 cells are more sensitive to inhibition of Plk1 than AR of LNCaP cells. LNCaP or C4-2 cells were treated with MG132 ± BI2536 and harvested. H, inhibition of Plk1 decreases the level of nuclear AR. After LNCaP cells were treated with 100 nM of BI2536 for 2 hours, lysates were subjected to subcellular fractionation to obtain cytoplasmic (C) and nuclear (N) fractions, followed by anti-AR IB. Only halves of cytoplasmic fractions were loaded due to the limited volumes of gel wells. I, inhibition of Plk1 decreases AR expression under oxidative stress. LNCaP cells were incubated with 100 nM of BI2536 for 8 hours, treated with 1 mM of H₂O₂ or 1 mM of diamide for 5 minutes, and harvested for subcellular fractionation. Cytoplasmic and nuclear fractions were analyzed by anti-AR IB. Only halves of cytoplasmic fractions were loaded due to the limited volumes of gel wells. To quantify, we set the intensities of non-BI2536-treated lanes to be 1.0. J, inhibition of Plk1 decreases nuclear AR intensity.
LNCaP cells were pre-incubated with or without 100 nM of BI2536 for 2 hours, treated with 100 nM of DHT (dihydrotestosterone) for 2 hours, and harvested for anti-AR immunofluorescent (IF) staining. K, BI2536 inhibits AR activity. LNCaP cells were treated with different concentrations of BI2536, followed by luciferase assay to measure AR activity. L and M, inhibition of the PI3K/AKT/mTOR pathway antagonizes the oxidative stress-induced activation of AR. LNCaP (L) and C4-2 (M) cells were pre-incubated with the PI3K/AKT/mTOR pathway inhibitors (25 µM of LY294002 for 1 hour, 5 µM of MK-2206 for 2 hours, or 100 nM of rapamycin for 2 hours), treated with 1 mM of H2O2 for 5 minutes, and harvested. N, inhibition of Plk1 and AKT reduced the level of nuclear Twist protein in C4-2 cells. O, BI2536 inhibits Twist1 activity. C4-2 cells were treated with BI2536 (10 nM, 12 hours), MK2206 (20 nM, 6 hours), insulin (1 nM, 6 hours) or BI2536 plus insulin, and harvested for RT-PCR to measure mRNA levels of CLU (clusterin) and AR, two transcription targets of Twist1.

**Figure 3.** Plk1 affects lipid metabolism in PCa. A, inhibition of Plk1 reduces the active (cleaved) form of SREBP2. LNCaP and C4-2 cells were treated with BI2536 and harvested for IB. B, inhibition of Plk1 reduces the active (cleaved) form of SREBP1. C4-2 cells were treated with BI2536, followed by subcellular fractionation. C and D, inhibition of Plk1 decreases the protein levels of active forms of SREBP1/2 in PC3 and DU145 cells. Cells were treated with or without 100 nM of BI2536 for 12 hours and harvested for IB with antibodies against SREBP2 (C) or SREBP1 (D). E and F, BI2536 inhibits the SREBP pathway. E, LNCaP (top panel) and C4-2 (bottom panel) cells were treated with 10nM BI2536 for 4 hours or 24 hours, and harvested for real-time qPCR to measure the mRNA levels of three SREBP-regulated genes. FAS: fatty acid synthase, MVK: mevalonate kinase, HMGCR: 3-hydroxy-3-methyl-glutaryl-CoA reductase. F, PC3 and LNCaP cells were treated with BI2536 and harvested for IB. G, BI2536 inhibits phosphorylation of GSK3β. Cells were treated with BI2536 and harvested. H, Plk1 inhibition-induced reduction of AR and FAS levels occurs before massive apoptosis. LNCaP cells were treated with BI2536 for different time and harvested for
IB. I, inhibition of Plk1 blocks the accumulation of cholesterol ester (CE) in PC3 cells. PC3 cells were treated with different concentrations of BI2536 for 60 hours and subjected to Raman microscopic analysis. The arrow at bottom indicates the 702 cm\(^{-1}\) peak due to cholesterol ring vibration. J, overexpression of Plk1 increases CE accumulation. PC3 cells were infected with GFP-Plk1-expressing lentivirus for 24 hours or 48 hours and subjected to Raman microscopic analysis. The ratio of intensity of the CE peak 702 cm\(^{-1}\) versus intensity of the peak 1442 cm\(^{-1}\) in each cell was calculated. Ten cells from each group were randomly selected for CE measurement. K and L, oxidative stress increases CE accumulation. LNCaP cells were treated with or without 1 mM of diamide for 5 minutes and subjected to Raman microscopic analysis. Ten cells from each group were randomly chosen to calculate the ratio of intensity of the CE peak 702 cm\(^{-1}\) versus intensity of the peak 1442 cm\(^{-1}\) in each cell. M, inhibition of steroidogenesis antagonizes oxidative stress-induced AR elevation. LNCaP cells, growing in RPMI-1640 medium with 5% Charcoal-stripped fetal bovine serum (CS-FBS), were pre-incubated with 1 µM of abiraterone for 24 hours, treated with 20 µM of DPI for 12 hours or 1 mM of H\(_2\)O\(_2\) for 5 minutes, and harvested for anti-AR IB. N and O, inhibition of lipid rafts decreases activation of AKT. PC3 (N) or DU145 (O) cells were pre-incubated with 2 µg/ml of filipin for 1 hour, treated with 1 mM of H\(_2\)O\(_2\) for 5 minutes, and harvested for anti-p-AKT IB.

**Figure 4.** Inhibition of Plk1 enhances cellular response to ASI in PCa cells. A-C, AR and AR-vs regulate Plk1. A, expression of AR increases the level of Plk1 in AR-null cells. PC3 cells were transfected with AR and harvested for RT-PCR. B, depletion of AR reduces the levels of Plk1 in AR-positive cells. LNCaP or C4-2 cells were transfected with shRNA to deplete AR and harvested for IB. C, depletion of AR-vs reduces the level of Plk1. 22Rv-1 cells were transfected with shRNA to deplete AR-v1 or AR-v7, treated with nocodazole, and harvested for IB (top panel) or RT-PCR (bottom panel). D and E, BI2536 and abiraterone inhibit AR signaling in a synergistic manner. C4-2 (D) and 22Rv1 (E) CRPC cells were treated with BI2536 (10 nM), abiraterone (10 µM) or both for 24 hours, and harvested for IB. F-H, BI2536 and enzalutamide
inhibit AR signaling synergistically. C4-2 (F) and 22Rv1 (G, H) cells were treated with BI2536 (10 nM), enzalutamide (10 µM) or both for 24 hours, and harvested for IB (F, G) or FACS (H). I, LNCaP cells were treated with BI2536 (10 nM), enzalutamide (10 µM) or both for 24 hours, then treated with R1881 for 2 hours, and harvested for anti-AR IF staining. J, the combination index of BI2536 and enzalutamide in LNCaP cells. K, Plk1 transcription is regulated by AR signaling. LNCaP cells were growing in different conditions (CSS media and treated with R1881 or FBS-containing media and treated with MDV3100), and harvested for RT-PCR.

**Figure 5.** Inhibition of Plk1 sensitizes MR49F cells to enzalutamide. A, MR49F cells were treated with BI2536 (10 nM), enzalutamide (10 µM) or both for 24 hours, and harvested for IB. B, MR49F cells were treated with indicated concentrations of BI2536 and enzalutamide. C, cells in A were harvested for FACS analysis. D, MR49F cells as in A were treated with R1881 for 2 hours, and harvested for anti-AR IF staining.

**Figure 6.** BI2536 and abiraterone inhibit LuCaP35CR xenografts synergistically. LuCaP35CR tumors were inoculated into nude mice, which had been castrated 2 weeks ahead. After waiting for several weeks for tumors to reach 250 to 300 mm$^3$, mice were intravenously injected twice per week with BI2536 (10 mg/kg), abiraterone (50 mg/kg) or both, and followed for additional 43 days. A, tumor growth curves of the study. B, tumor weight measurement after being freshly removed from the bodies. C, images of the mice at the end of the study. D, inhibition of PSA level by BI2536 and abiraterone. Blood was collected once a week and serum PSA level was measured using the PSA ELISA kit. E, The levels of testosterone was measured by mass spectrometry as described (43). F, the levels of lipid droplets in LuCaP35CR tumors were measured by label-free Raman spectromicroscopy as described (8).

**Figure 7.** A proposed working model. The level of cholesterol is regulated by 1) homoeostasis by SREBP-1/2, 2) neosynthesis by HMGCoA-R; 3) uptake by LDL-R; 4) esterification by ACAT; and 5) CE hydrolysis by nCEH. ACAT: acyl-CoA:cholesterol acyltransferase, CE: cholesteryl esters, LDL-R: low-density lipoprotein receptor.
density lipoprotein receptor, nCEH: neutral cholesterol ester hydrolase, SREBPs: the sterol regulatory element binding proteins, SCAP: SREBP-cleavage-activating protein.
References:


Figure 2
Figure 3
Figure 4

(A) PC3 and PC3 AR β-actin

(B) C4-2 and LNCaP shAR AR Plk1 β-actin

(C) 22Rv-1 Noc. Plk1 β-actin

(D) Abiraterone BI2536 AR Actin

(E) Abiraterone BI2536 22Rv1 AR AR-v AR Actin

(F) C4-2 BI2536 MDV3100 AR Actin

(G) 22Rv1 BI2536 MDV3100 AR AR-v Actin

(H) 22Rv1 Control MDV3100 BI2536 MDV3100 + BI2536

(I) LNCaP DAPI AR Merge

(J) LNCaP Drugs IC50

<table>
<thead>
<tr>
<th>Drugs</th>
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<tr>
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<tr>
<td>MDV3100</td>
<td>10.4 µM</td>
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<tr>
<td>BI2536 + 5µM MDV3100</td>
<td>10 nM</td>
</tr>
<tr>
<td>MDV3100 + 50 nM BI2536</td>
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Combination index = 0.12

(K) Plk1 PSA

Relative mRNA Level

CSS+R1881 FBS+MDV3100 CSS+R1881 FBS

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Figure 6

A

B

C

D

E

F

Lipid droplets in LuCaP35CR tumors
Figure 7

Castration

Oxidative stress

NF-κB

PI3K

β2536

The PI3K pathway

AKT

MK2206

mTOR

GSK3β

 Twist1

Androgen

AR

SCAP

SREBPs

FAS

HMGCyA-R

LDL-R

Fatty acid

Cholesterol

De novo steroidogenesis

Abiraterone

Androgen

AKT activation

CRPC

AR

MDV3100

ACAT1/2

nCEH

CE

Lipid raft

Filipin
Plk1 inhibition enhances the efficacy of androgen signaling blockade in castration-resistant prostate cancer

Zhe Zhang, Xianzeng Hou, Chen Shao, et al.

Cancer Res Published OnlineFirst September 24, 2014.

Updated version
Access the most recent version of this article at: doi:10.1158/0008-5472.CAN-14-1916

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