Generation 2.5 Antisense Oligonucleotides Targeting the Androgen Receptor and Its Splice Variants Suppress Enzalutamide-Resistant Prostate Cancer Cell Growth

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Abstract

Purpose: Enzalutamide (ENZ) is a potent androgen receptor (AR) antagonist with activity in castration-resistant prostate cancer (CRPC); however, progression to ENZ-resistant (ENZ-R) CRPC frequently occurs with rising serum PSA levels, implicating AR full-length (ARFL) or variants (AR-Vs) in disease progression.

Experimental Design: To define functional roles of ARFL and AR-Vs in ENZ-R CRPC, we designed 3 antisense oligonucleotides (ASO) targeting exon-1, intron-1, and exon-8 in AR pre-mRNA to knockdown ARFL alone or with AR-Vs, and examined their effects in three CRPC cell lines and patient-derived xenografts.

Results: ENZ-R-LNCaP cells express high levels of both ARFL and AR-V7 compared with CRPC-LNCaP; in particular, ARFL levels in ENZ-R-LNCaP cells express high levels of both ARFL and AR-V7 compared with CRPC-LNCaP; in particular, ARFL levels were approximately 12-fold higher than AR-V7. Both ARFL and AR-V7 are highly expressed in the nuclear fractions of ENZ-R-LNCaP cells even in the absence of exogenous androgens. In ENZ-R-LNCaP cells, knockdown of ARFL alone, or ARFL plus AR-Vs, similarly induced apoptosis, suppressed cell growth and AR-regulated gene expression, and delayed tumor growth in vivo. In 22Rv1 cells that are inherently ENZ-resistant, knockdown of both ARFL and AR-Vs more potently suppressed cell growth, AR transcriptional activity, and AR-regulated gene expression than knockdown of ARFL alone. Exon-1 AR-ASO also inhibited tumor growth of LTL-313BR patient-derived CRPC xenografts.

Conclusions: These data identify the AR as an important driver of ENZ resistance, and while the contributions of ARFL and AR-Vs can vary across cell systems, ARFL is the key driver in the ENZ-R LNCaP model. AR targeting strategies against both ARFL and AR-Vs is a rational approach for AR-dependent CRPC.

Clinical Cancer Research: Preclinical

Introduction

First-line treatment for metastatic prostate cancer is androgen deprivation therapy (ADT), which reduces serum testosterone levels and androgen receptor (AR) activity. Despite high initial response rates, remissions are temporary with emergence of castration-resistant prostate cancer (CRPC), largely driven by AR reactivation despite low levels of serum testosterone. Serum prostate-specific antigen (PSA) is an AR-regulated protein that serves as a useful marker of response and prognosis to ADT (1); indeed, rising PSA is the earliest sign of CRPC (2, 3). AR reactivation in CRPC involves AR gene amplification, mutations or splice variants (AR-Vs), as well as intratumoral steroidogenesis, increased coactivator expression, and activation of signal transduction pathways that sensitize AR to low levels of androgens (4–7). These mechanisms work in concert to drive CRPC progression, and highlight that targeting the AR remains a critical component of novel CRPC therapies (8, 9).

More potent AR pathway inhibitors like abiraterone (10, 11) and enzalutamide (ENZ; refs. 12, 13) suppress ligand levels and binding to AR, respectively, inhibiting AR nuclear translocation and transcriptional activity. While these AR pathway inhibitors significantly prolong survival in CRPC, cancers often recur with rising serum PSA levels indicative of persistent AR activity. Therefore, loss of suppression of AR activity despite potent AR pathway inhibition remains a major problem in CRPC and additional novel agents with activity in abiraterone- or ENZ-resistant tumors is critical to improve control of CRPC.

Antisense oligonucleotides (ASO) offer one approach to selectively target genes and their splice variants. While ASOs are primarily used to inhibit "undruggable" targets (14, 15), they may also be of use against drug-resistant targets like nuclear AR in ENZ-resistance (ENZ-R). While AR extinction approaches using

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ASOs (16) or shRNA (17) can reduce AR levels and inhibit tumor growth in CRPC models, they have not been studied in the context of ENZ-R disease and their knockdown effects on full-length AR (ARFL) and AR-Vs are undefined. This is particularly important as AR-Vs are emerging as a mechanism driving ligand-independent and ENZ-R AR transcription (18–20). This could be targeted with appropriately designed ASO.

In this study, we characterized changes in ARFL and AR-Vs levels associated with ENZ treatment response and resistance, and compared effects of AR-ASOs targeting either ARFL or AR-Vs and AR-Vs. ENZ exposure induces expression of both ARFL and AR-V7 in CRPC, and high levels of ARFL and AR-V7 are associated with ENZ-R CRPC. However, ARFL mRNA levels are 12 times higher than AR-V7. Despite differential effects on AR-Vs knockdown, all AR-ASO potently silenced ARFL levels and similarly induced apoptosis and cell growth inhibition in ENZ-R LNCaP cells. In contrast, knockdown of both ARFL plus AR-Vs more potently suppressed 22Rv1 cell growth, AR transcriptional activity, and AR-regulated gene expression, compared with knockdown of ARFL alone. Overall, these results highlight ARFL as an important driver of ENZ-R CRPC and that while both ARFL and AR-V7 levels are induced during the evolution to ENZ-R, their biologic effects appear cell line and context dependent.

Materials and Methods

Cell lines
LNCaP cells were provided by Dr. Leland W.K. Chung (1992, MD Anderson Cancer Center, Houston, TX) and authenticated with short tandem repeat (STR) profile analysis at Genetics Resources Core Facility (GRCF) at John Hopkins (Baltimore, MD) in January 2013. PC-3 and 22Rv1 cells were obtained from ATCC and authenticated at GRCF in January 2013 and at IDEXX BioResearch in September 2014, respectively. M12 cells stably expressing AR-V567es cDNA (M12 AR-V567es) were provided by Dr. Stephen R. Plymate (University of Washington School of Medicine, Seattle, WA) and authenticated at GRCF in September 2014, respectively, with 5% FBS. M12 AR-V567es stable cells were cultured as described previously (5, 21).

Generation of castration- and ENZ-R LNCaP xenografts and cell lines
CRPC and ENZ-R LNCaP xenografts and cell lines were generated as previously described (22–24). The ENZ-R LNCaP cell lines MR1F, MR57A, MR49F, and MR49C were maintained in RPMI1640 with 10 μmol/L ENZ (Haoyuan Chemexpress Co.) + 5% FBS; CRPC LNCaP vehicle-treated tumors maintained in RPMI1640 with 5% charcoal-stripped serum (CSS). The authentication of MR49F, MR49C, and VehD was performed at GRCF in January of 2013; the other lines were not authenticated.

Molecular profiling
Transcriptome sequencing was performed using Illumina GA-II (Michael Smith Genome Sciences Centre, Vancouver, British Columbia, Canada) in four ENZ-R LNCaP and two CRPC LNCaP xenografts using established protocols (25). We used TopHat (26) to map RNA-Seq reads to the genome (hg19). Determination of AR expression (including splice variants) and an estimate of the ratio of AR-V7 to ARFL are shown in Supplementary Materials and Methods.

Genome copy number profiling was performed on Agilent SurePrint G3 Human CGH Microarray Kit, 4 × 180 K in 4 ENZ-R LNCaP and 2 CRPC LNCaP xenografts tumors as described previously (27). Array CGH copy number data are available at GEO accession number GSE55345. To test for the F876L mutation, we performed PCR and Sanger sequencing across exon 8 of the AR gene in genomic DNA from the MR49F cell line, using standard techniques.

Antisense, siRNA, and plasmid transfection
Antisense AR (AR-ASO) used in this study contain constrained-ethyl (cEt) chemistry (Gen 2.5) and were identified by screening over 1400 ASOs against the full-length AR genomic sequence. The AR-ASO targeting exon-1, intron-1, exon-8, and scrambled (SCR) control sequences were 5'-GGCCGACTACTACACCT-3', 5'-CAACCTATTAAATCAC-3', 5'-GCCCGCGGAAGTTTAG-3', and 5'-CAGCGCTGACAACAGTTTCAT-3', respectively. SCR oligonucleotides with the same chemistry were supplied by ISIS Pharmaceuticals. Prostate cells were treated with oligonucleotides using protocols described previously (28, 29). For siRNA transfection, cells were treated with AR Exon 2b (30), AR Exon CE3 (31), or Scramble siRNA using Lipofectamine as described previously (28). AR-V7 plasmid (a generous gift from Dr. Stephen R. Plymate, University of Washington School of Medicine, Seattle, WA) was transfected using Lipofectin following the manufacturer's protocol.

Western blot analysis
Total proteins were extracted using radioimmunoprecipitation assay buffer and submitted to Western blot analysis as previously described (32). Primary antibodies are shown in Supplementary Materials and Methods. NuCLEAR Extraction Kit (Sigma-Aldrich) was used according to manufacturer's protocol.

Quantitative reverse transcription-PCR
Total RNA was extracted using TRIzol (Invitrogen Life Technologies, Inc.), respectively, with 5% FBS. M12 AR-V567es stable cells were cultured as described previously (5, 21).
Table S1) were normalized to β-actin levels as an internal standard, and the comparative cycle threshold (Ct) method was used to calculate relative quantification of target mRNAs. Each assay was conducted in triplicate.

AR transcriptional activity
Cells were seeded at a density of 2.5 × 10^4 in 6-well plates and treated with AR-ASO or SCRB in CSS media. The next day, cells were transfected with ARR-3 luciferase reporter along with Remilla plasmid as described previously (29). All experiments were carried out in triplicate.

Cell proliferation and cell-cycle assays
Cells were cultured in CSS media, transfected with AR-ASO or SCRB, and cell growth measured by crystal violet assay as previously described (33). Cell-cycle distribution was analyzed by flow cytometry (Beckman Coulter Epics Elite, Beckman, Inc.) as described previously (29). Each assay was done in triplicate three times.

In vivo studies
Athymic mice were castrated and inoculated subcutaneously with 2 × 10^5 ENZ-R MR49F cells; mice were treated with ENZ 10 mg/kg each po daily for maintenance of ENZ resistance. Once tumors reached 200 mm^3, mice were randomly assigned to 12.5 mg/kg each po AR-ASO or SCRB for 3 days per week thereafter. Each experimental group consisted of 11 mice. Tumor volume and serum PSA were measured as previously described (29). When tumor volume reached 10% or more of body weight, mice were sacrificed and tumors were harvested for evaluation of protein expression by Western blot analyses, mRNA expression by real-time monitoring of PCR, and immunohistochemistry. All animal procedures were carried out according to the guidelines of the Canadian Council on Animal Care and appropriate institutional certification.

Patient-derived LLT-313BR CRPC xenograft tumors (www.livingtumorlab.com) were grafted under the renal capsules as previously described (34). Once tumors reached palpable, mice were randomly assigned to 40 mg/kg exon-1 AR-ASO or SCRB. Each experimental group consisted of 9 mice. PSA was measured on days 17 and 24. Tumors were harvested on day 24 and tumor volume and tumor weights were measured as previously described (34).

Immunohistochemistry
Immunohistochemistry was performed as previously described previously (29).

Statistical analysis
All in vitro data were assessed using the Student t test and one-way ANOVA test. Tumor volume and serum PSA levels of mice were assessed in several ENZ-R cell lines. ARFL and AR-V7 protein (Fig. 1A, left) and mRNA (Fig. 1A, right) levels were increased in ENZ-R LNCaP-derived cell lines compared with CRPC LNCaP-derived (VehD and VehA) cells; moreover, short-term ENZ treatment induced ARF3 and AR-V7 mRNA levels in parental LNCaP cells (Supplementary Fig. S1). AR-V7 protein levels, however, were much lower than ARF3 protein levels and most apparent on Western blot analysis with prolonged exposure (Fig. 1A, left).

Next, levels of ARF3 and AR-V7 were assessed in several ENZ-R xenografts. Quantitative RT-PCR (Fig. 1B) and RNA seq (Fig. 1C, left) demonstrated higher ARF3 and AR-V7 mRNA levels in tumor tissues from ENZ-R LNCaP xenografts compared with CRPC LNCaP xenografts; however, ARF3 mRNA levels were approximately 12-fold higher than AR-V7, as assessed by RNA seq (Fig. 1C, right).

While transcriptome sequencing detected many AR-Vs in tumor tissues from ENZ-R LNCaP xenografts, only AR-V7 was predominately expressed (35). Recent reports have linked a mutation in the ligand-binding domain of AR (F876L) to ENZ resistance (36–38). This mutation was not detectable by RNA-Seq in the ENZ-R LNCaP xenografts. However, PCR and Sanger sequencing across the AR ligand-binding domain in MR49F cells was positive for the F876L mutation, as well as the parental T877A mutation. DNA copy number analysis revealed an absence of focal AR amplification (ref. 39; Supplementary Fig. S2A). Therefore, high AR mRNA expression appears independent of genetic alterations, potentially indicating epigenetic mechanisms of upregulation and epithelial plasticity. The integrative genome viewer (IGV) analysis on mRNA sequencing data across exon 8 of the AR has been performed in LNCaP-derived MR49F and VehD CRPC cells as well as LLT-313BR tumors. It shows that MR49F carries the F876L mutation at a frequency of 63% (blue) and there is no detection of mutation F876L in LLT-313BR and VehD CRPC. As a control, the native LNCaP T877A mutation (orange) is clearly present in 100% of reads (Supplementary Fig. S2B).

Subcellular fractionation studies detected higher levels of both ARF3 and AR-V7 proteins in the nucleus in MR49F compared with parental LNCaP in response to ENZ treatment (Fig. 1D). Importantly, this high nuclear accumulation of ARF3 is seen even in the absence of exogenous androgens, suggesting that ARF3 is driving ENZ resistance. Immunohistochemical analysis also demonstrated higher levels of ARF3 in the nucleus of ENZ-R compared with castrate-resistant LNCaP tumors (Supplementary Fig. S3). Collectively, these data indicate that ENZ induces increased expression levels of ARF3 and AR-V7, and both are associated with development of ENZ resistance in the LNCaP model. However, although levels of AR-V7 are low compared with ARF3, the latter is localized in both cytoplasm and nucleus of ENZ-R LNCaP cells, while AR-V7 is confined almost exclusively to the nuclear fraction.

AR-ASO knockdown of ARF3 and AR-Vs
To define the functional role of ARF3 and AR-Vs in ENZ resistance, 3 ASO sequences were designed to target exon-1, intron-1, or exon-8 in AR pre-mRNA (Fig. 2A) to selectively knockdown ARF3 alone, or knockdown ARF3 plus AR-Vs simultaneously. All three AR-ASO dose dependently decreased ARF3 in both parental LNCaP (Supplementary Fig. S4A) and ENZ-R LNCaP MR49F (Fig. 2B, top) and MR1F (Supplementary Fig. S4B). As AR-Vs are COOH-truncated, exon-1 and intron-1 AR-ASOs potently suppressed levels of ARF3 and AR-V7, whereas exon-8 AR-ASO only reduced levels of...
While all 3 ASO potently reduced ARFL levels, only exon-1 and intron-1 AR exhibit relatively low levels of AR activity and PSA expression. mRNA levels (Fig. 2B, bottom). exon-1 and intron-1 AR-ASO, but not exon-8, reduced AR-V7 ARFL. Quantitative real-time PCR analysis confirmed that both exon-1 and intron-1 AR-ASO, but not exon-8, reduced AR-V7 mRNA levels (Fig. 2B, bottom).

22Rv1 cells express high levels of endogenous AR-Vs, but exhibit relatively low levels of AR activity and PSA expression. While all 3 ASO potently reduced ARV7 levels, only exon-1 and intron-1 AR-ASO dose dependently reduced AR-V7s; in contrast and similar to LNCaP-derived ENZ-R cell lines, exon-8 AR-ASO did not alter AR-V7s protein levels (Fig. 2C, top). Quantitative real-time PCR indicated that AR-V7 mRNA was decreased by exon-1 and intron-1 AR-ASO but not by exon-8 AR-ASO (Fig. 2C, bottom).

M12 prostate cancer cells, which are engineered to stably express AR-V567es, were used to further assess differential effects of the 3 AR-ASO on silencing AR-V567es. As expected, only exon-1 AR-ASO decreased AR-V567es protein and mRNA levels (Fig. 2D). Intron-1 ASO did not silence AR-V567es because the construct lacks intron-1.

**Effects of AR-ASO on AR-regulated genes and AR transcriptional activity**

Differential knockdown of AR-Vs by exon-1 versus exon-8 AR-ASO was used to evaluate their relative contribution to the overall AR-regulated transcriptome in ENZ-R LNCaP (MR49F) and 22Rv1 cells. Quantitative real-time PCR was used to measure expression levels of several AR-regulated genes, PSA, FKBP5, TMPRSS2, and NKK3.1. In MR49F cells, all three AR-ASO similarly decreased the basal mRNA levels of these AR-regulated genes (Fig. 2B, bottom). Both exon-1 and exon-8 AR-ASO also potently suppressed AR-V7 mRNA expression in ENZ-R LNCaP cells, but only AR-V7 was overtly expressed. AR-V7 mRNA expression (C, left) and mean ratio (C, right) were examined in ENZ-R LNCaP xenograft tumors. Please note that the F876L mutation was not detectable in the ENZ-R LNCaP xenograft tumors. D, LNCaP and MR49F cells were cultured for 3 days in media supplemented with CSS and ENZ followed by 1 nmol/L R1881. Cells were harvested and fractioned into nuclear and cytoplasmic extracts, protein extracts were analyzed by Western blotting for ARV7 and AR-V7. Lamin B1 and α-tubulin are shown as markers for nuclear and cytoplasm, respectively. **P < 0.001; ***P < 0.01; ****P < 0.0001, *P < 0.05.

**Effects of AR-ASO on cell growth and apoptosis**

Differential knockdown of AR-V7 and AR-Vs by exon-1 versus exon-8 AR-ASO was used to evaluate relative biologic contributions of AR-V7 versus AR-V7 in regulating ENZ-R LNCaP and 22Rv1 cell survival and growth. Cell growth assays were performed in castrate-sensitive LNCaP, 4 different ENZ-R LNCaP-derived cells,
Figure 2.
Effects of AR-ASO on AR-FL, AR-Vs, AR-regulated gene expression levels and AR transcriptional activity in ENZ-R LNCaP and 22Rv1 cells. A, three AR-ASO sequences were designed to target exon-1, intron-1, and exon-8 in AR. B, MR49F cells were treated for 48 hours in media with ENZ supplemented with CSS with the indicated AR-ASO. (Continued on the following page.)
22Rv1, and AR-negative PC3 cell lines (as controls). As expected, AR-ASO treatment did not affect PC-3 cell growth over the concentrations used. Despite differential effects on ARFL and AR-V knockdown (Fig. 2B and Supplementary Fig. S4), all AR-ASO similarly inhibited castrate-sensitive and ENZ-R LNCaP cell growth (Fig. 3A). Exon-1 and exon-8 AR-ASO similarly induced apoptosis in ENZ-R cells as measured by caspase-3 and PARP cleavage (Fig. 3B). The fraction of ENZ-R LNCaP cells undergoing apoptosis (sub-G1 fraction) was similarly increased by exon-1 and exon-8 AR-ASO, and was accompanied by cell-cycle arrest (Fig. 3C, left) and decreased levels of cell-cycle proteins, CDK4, and cyclin D1 (Fig. 3C, right). These data suggest that, as both AR-ASO similarly silenced ARFL levels, inhibited cell growth, and induced apoptosis in LNCaP-derived ENZ-R despite differential effects on

(Continued) ARFL, AR-V7, PSA and vinculin protein were analyzed by Western blotting. ARFL, AR-V7, and AR regulated target mRNA expression were analyzed by quantitative real-time PCR. AR-V7 protein was detected with anti-AR-V7 monoclonal antibody. C, 22Rv1 cells were treated for 48 hours in CSS media with 3 types of AR-ASO and ARFL, AR-Vs, and β-actin protein were analyzed by Western blotting and ARFL, AR-V7, and AR regulated target mRNA expression were analyzed by quantitative real-time PCR. AR proteins was detected with AR N-20 antibody, which detects both ARFL and AR-Vs. D, M12 cells stably expressing AR-V567es were treated for 48 hours with the AR-ASO and protein and mRNA extracts were analyzed by Western blotting and real-time PCR for AR-V567es. AR-V567es protein (80 kDa) was detected with AR N-20 antibody. E, MR49F cells were treated with 100 nmol/L AR-ASO in CSS media with ENZ. F, 22Rv1 cells were treated with 100 nmol/L AR-ASO in CSS media. The next day, cells were transiently transfected with 1 μg of ARR-3-luciferase, followed by 1 nmol/L R1881 treatment for 12 hours and luciferase activity was determined. **, P < 0.01; *, P < 0.05.

Figure 3. Exon-1 and -8 AR-ASO similarly inhibit cell growth and induce apoptosis in ENZ-R LNCaP cells. A, AR-positive LNCaP, four ENZ-R derived LNCaP cell lines, and AR-negative PC3 cell lines were cultured in CSS media for 96 hours with the indicated AR-ASO. Cell growth was determined by crystal violet assay and compared with SCRB. B, MR49F cells were treated in CSS media with exon-1 and -8 AR-ASO for 96 hours and PARP and caspase-3 expression levels were measured by Western blotting. C, MR49F cells were treated in CSS media with exon-1 and -8 AR-ASO for 96 hours and the proportion of cells in sub-G1, G0-G1, S, and G2-M was determined by propidium iodide staining (left). C, right, MR49F cells were treated with exon-1 and -8 AR-ASO for 96 hours and CDK4 and Cyclin D1 expression levels were measured by Western blotting. D, 22Rv1 cells were cultured in CSS media for 96 hours with the indicated AR-ASO and cell growth was determined by crystal violet assay and compared with SCRB. **, P < 0.05.
Figure 4.
Relative role of AR<sub>FL</sub> versus AR-V in AR activity after transient transfection of AR-V7 in MR49F LNCaP cells. MR49F cells were transiently transfected with empty vector or AR-V7 cDNA and then treated in CSS media with exon-1 and -8 AR-ASO for 72 hours. A, AR-FL, AR-V, PSA, and β-actin protein expression levels were measured by Western blotting (left). (Continued on the following page.)
AR-V knockdown, most AR pathway-derived cytoprotection is driven by AR-FL in ENZ-R LNCaP model. In 22Rv1 cells, however, knockdown of both AR-FL and AR-Vs more potently suppressed cell growth compared with knockdown of AR-FL alone, suggesting a significant role for AR-Vs in this cell system (Fig. 3D). As ENZ-R LNCaP cells express low levels of AR-V7 (~8%) compared with AR-FL, we transiently transfected AR-V7 in MR49F cells to further assess relative role of AR-FL versus AR-V in AR pathway activation in ENZ-R LNCaP cells. Transient transfection of AR-V7 increased levels of ligand-independent AR transactivation (Supplementary Fig. S5). Exon-1 ASO reduced both AR-FL and AR-V7 levels (Fig. 4A), and more potently suppressed FKBP5 mRNA expression (Fig. 4B) and AR transactivation (Fig. 4C) compared with exon-8 AR-ASO. However, exon-1 and 8 AR-ASO treatment in ENZ-R LNCaP AR-V7-overexpressing cells similarly decreased PSA protein and mRNA expression (Fig. 4A and B), induced apoptosis as measured by caspase-3 and PARP cleavage (Fig. 4D) and cell growth inhibition (Fig. 4E). These results confirm that the biologic consequences of AR activity in ENZ-R LNCaP cells are principally driven by AR-FL and suggest that some AR target genes such as FKBP5 may be preferentially regulated by AR-V7.

Effects of specific AR-V silencing in ENZ-R LNCaP and 22Rv1 cells

While ENZ-R LNCaP cells express low levels of AR-V7 compared with AR-FL, this variant always exists in nucleus and has constitutive ligand-independent activity. ENZ-R LNCaP cells

(Continued) A, AR-FL, AR-V7 mRNA extracts were analyzed by quantitative real-time PCR (right). B, AR-regulated mRNA extracts were analyzed by quantitative real-time PCR. C, the next day cells were transiently transfected with 1 μg of ARR-3-luciferase, followed in media with ENZ supplemented with CSS and luciferase activity was determined. D, following transient transfection with empty vector or AR-V7 cDNA and treatment in CSS media with exon-1 and -8 AR-ASO for 96 hours, PARP, and caspase-3 expression levels were measured by Western blotting. E, cell growth was determined by crystal violet assay and compared with SCR siRNA at the same concentration. *, P < 0.05; **, P < 0.01; ***, P < 0.001; ****, P < 0.0001.
Figure 6.
AR-ASO suppress ENZ-R LNCaP and patient-derived CRPC tumor growth in vivo. When MR49F xenograft tumors reached 200 mm³, mice were randomly assigned to 12.5 mg/kg exon-1, exon-8 AR-ASO or SCRB. The mean tumor volume (A, left) and the serum PSA level (A, right) were compared among the 3 groups \( \pm \) SEM (n = 11 per group). (Continued on the following page.)
expressed AR-V7 without DNA rearrangement while 22Rv1 cells have a rearrangement with 35 kb tandem duplication encompassing AR exon 3 and high expression of truncated AR-Vs AR1/2/3/2b and AR1/2/3/CE3 (AR-V7; refs. 20, 40). To further define the functional role of AR-Vs in ENZ-R LNCaP and 22Rv1 cells, we used a CE3 siRNA that specifically silenced AR-V7, but not ARFL, in ENZ-R LNCaP cells, and used CE3 and E2b siRNA to specifically silence AR-Vs in 22Rv1. In ENZ-R LNCaP cells, AR-V7 knockdown did not decrease PSA protein or mRNA levels, did not induce apoptosis as measured by caspase-3 and PARP cleavage (Fig. 5A, left and 5B left), and did not inhibit cell growth (Fig. 5C, left). In 22Rv1 cells, AR-V7 knockdown decreased PSA protein and mRNA levels, and induced apoptosis (Fig. 5A and B, right) and cell growth inhibition (Fig. 5C, right). These data indicate that the biologic consequences of AR-V are cell-type-specific, with 22Rv1 cells driven by AR-Vs (20), whereas ENZ-R LNCaP cells are driven predominantly by ARFL.

**AR-ASO inhibit ENZ-R LNCaP and patient-derived CRPC tumor growth in vivo**

The in vivo activity of exon-1 and exon-8 AR-ASO were evaluated using MR49F LNCaP xenografts. At baseline, mean tumor volume and serum PSA levels were similar in both groups. Exon-1 and Exon-8 AR-ASO significantly reduced mean tumor volume from 2,653 mm³ to 1,168 and 994 mm³ by 3 weeks (**, \( P < 0.01 \) and **, \( P < 0.01 \) respectively), compared with SCRB (Fig. 6A, left); serum PSA levels were also significantly lower (\( P < 0.05 \), **, \( P < 0.05 \); Fig. 6A, right). There was no significant difference between the two AR-ASO treatment groups. Waterfall plots of best tumor volume and serum PSA decline per mouse at any time are shown in Fig. 6B.

ARFL and PSA protein expression in tumors collected from representative MR49F xenografts (\( n = 4 \) per group) similarly decreased after treatment with exon-1 and exon-8 AR-ASO (Fig. 6C, left). Exon-1 ASO significantly decreased expression of both ARFL and AR-V7 mRNA; in comparison, exon-8 ASO significantly decreased ARFL, without reducing AR-V7 mRNA levels in tumors collected from MR49F xenografts (Fig. 6C, right). PSA mRNA levels were significantly decreased after treatment with both exon-1 and exon-8 AR-ASO compared with SCRB; mRNA levels of AR-regulated genes were also reduced (Fig. 6C, right) by both AR-ASOs. Immunohistochemical analysis revealed that tumors treated with exon-1 or -8 AR-ASO had significantly higher apoptosis rates than SCRB controls (Fig. 6D, right) as shown by increased TUNEL staining (Fig. 6D left). Collectively, these data suggest that exon-1 ASO reduced expression levels of ARFL and AR-V7 with suppression of ENZ-R LNCaP tumor growth and the biologic consequences of AR activity in ENZ-R LNCaP cells are principally driven by ARFL.

Next, the in vivo activity of exon-1 AR-ASO was evaluated in LTL-313BR patient-derived xenografts. At baseline, mean serum PSA levels were similar in both groups. Exon-1 AR-ASO significantly reduced mean tumor volume and tumor weight from 919 mm³ to 574 mm³ and from 1,463 mg to 841 mg by 24 days (**, \( P < 0.01 \); **, \( P < 0.01 \) respectively), compared with SCRB (Fig. 6E, left); serum PSA levels were also significantly lower (**, \( P < 0.01 \); Fig. 6E, right).

**Discussion**

The AR remains a central driver of CRPC progression following first-line ADT (17), resulting from AR gene amplification, promiscuous AR mutants, altered expression of coregulators, activation by oncogenic signaling pathways, and increased androgen biosynthesis (4–6, 41). ENZ is an AR antagonist that binds potently to its ligand-binding domain (LBD) to inhibit AR nuclear translocation and transactivation (12), and results in 37% reduction in risk of death in post-docetaxel CRPC (42). Despite this benefit, primary resistance to ENZ is observed in about 30% of patients, and acquired resistance develops in initial responders, often associated with reactivation of AR signaling and rising PSA levels (12, 13). One mechanism of persistent AR signaling in ENZ-resistant CRPC involves treatment-induced AR mutations in the LBD. We detected the F876L AR mutation, reported to be ENZ-specific, in the LBD of ARFL, in MR49F cells, which may contribute to ENZ resistance (36–38).

Another potential mechanism of persistent AR signaling in ENZ-resistant CRPC involves treatment-induced AR splicing to encode for transcriptionally active COOH-terminally truncated AR-V proteins containing the NH2-terminal and central DNA-binding domains that lack the LBD (30). AR-Vs facilitate ligand-independent transcriptional activity and cell growth in various model systems (4, 5, 30, 43). AR-V7 is one of the most studied AR-Vs and reported to be associated with recurrence following surgery (4) and poor survival (43) and accumulating evidence links AR-Vs with CRPC and resistance to AR pathway inhibitors like abiraterone (18) and ENZ (19, 20). AR-V overexpression has been reported to provide a growth advantage under castrate conditions (4, 5, 31).

While recent reports link AR-Vs to CRPC, the biologic significance of AR-Vs in AR-regulated cell survival and proliferation, independent of ARFL, remains a controversial issue of clinical relevance as new AR antagonists are designed to also inhibit AR-V activity. For example, the activity of AR-Vs has been reported to remain dependent on endogenous ARFL (44). Our study using ASO-directed knockdown also suggests that the biologic consequences of AR-V7 are cell–line–dependent, and driven mainly by ARFL in ENZ-R LNCaP cells. While we found AR-V7 expression is induced by ENZ and highly expressed in ENZ-R LNCaP cells, ARFL levels also increase and remain more than 12-fold higher than AR-V7 levels in all ENZ-R LNCaP cells. While ARFL silencing has been reported to increase AR-V7 levels (19), we did not detect increased AR-V7 expression in parental and ENZ-R LNCaP cells after treatment with exon-8 AR-ASO targeting only ARFL. We did, however, see increased AR-V7 after ARFL knockdown when AR-V7

(C) **Continued** Waterfall plots of greatest percent decline in tumor volume (B, left) and the serum PSA level (B, right) from baseline at any time. C, total proteins were extracted from 4 representative xenograft tumors from each group and ARFL and PSA were analyzed by Western blotting (left). C, mRNA were extracted from 11 xenograft tumors from each group and ARFL, AR-V7, and AR regulated mRNA were analyzed by quantitative real-time PCR (right). D, tumors (\( n = 11 \) per group) were collected and TUNEL was evaluated by immunohistochemistry. E, when patient-derived CRPC xenograft tumors became palpable through the abdominal wall, mice were randomly assigned to 40 mg/kg exon-1 or SCRB. The mean tumor volume and tumor weight (E, left) and the serum PSA level (E, right) were compared between the 2 groups (mean ± SEM (\( n = 9 \) per group)). **, \( P < 0.01 \); *, \( P < 0.05 \).
was transiently transfected, which may reflect challenges with
detecting induction when initial AR-V7 levels are very low and
AR FL knockdown induces apoptosis.

To define the biologic consequences of AR FL and AR-V7 induc-
tion in ENZ resistance, ASOs were designed to suppress both AR FL
and AR-Vs, or AR FL alone. Despite differential effects on AR-V
knockdown, all AR-ASO potently silenced AR FL, levels and si-
larly induced apoptosis and inhibited cell growth in LNCaP-
derived ENZ-R cell lines. These data suggest that while ENZ
induces both AR FL and AR-V7 levels, the biologic conse-
quences are mainly driven by AR FL in the ENZ-R LNCaP model (44).
On the other hand, in 22Rv1 cells endogenously expressing higher
AR-Vs levels and lower AR FL levels, exon-1 AR-ASO more potently
suppressed endogenous AR FL and AR-V7 expression levels, cell
growth, AR transcriptional activity, and AR-regulated gene expres-
sion compared with exon-8 ASO. Cell line dependence may
partially explain this disparate data regarding biologic relevance of
AR FL versus AR-Vs in CRPC cell survival and AR pathway inhibitor
resistance. 22Rv1 cells contain an intragenic rearrangement of AR
with tandem duplication encompassing AR exon 3 and high
expression of AR-Vs (20, 39). Compared with LNCaP cells, AR
signaling in 22Rv1 is regulated to a much greater extent by AR-Vs,
possibly reflecting structural AR gene alterations in 22Rv1 than in
LNCaP (20, 39). A recent study evaluated the roles of AR FL and AR-
V species in CRPC ENZ responsiveness in the context of rearrange-
ment-driven changes in AR splicing (20). Unlike CRPC LNCaP-
derived cells, 22Rv1 cells display robust growth under castrate
conditions and ENZ treatment, despite inhibition of AR-regulated
genes. Knockdown of AR-Vs, but not full-length AR, reduced the
androgen-independent growth rate of 22Rv1 cells (20).

Although, AR targeting approaches with ASOs or siRNA have
been reported previously (16, 45, 46), no study so far has reported
on pharmacologic AR inhibition in vivo in the context of ENZ-
resistant disease. ASOs are chemically modified stretches of single
stranded DNA complementary to an mRNA region in a target gene
that inhibit gene expression by forming RNA/DNA duplexes that
are then degraded (15). Short tissue half-life of first-generation
phosphorothioate ASO, along with in vivo delivery of siRNA,
remain significant barriers to clinical development of ASO or
siRNA targeting the AR. In this study, we used a panel of highly
optimized, next-generation constrained-ethyl (cEt) modified
ASOs (Gen 2.5), which demonstrated favorable physicochemical,
biochemical, and pharmacokinetic properties in vivo (47, 48).
The improved resistance against nuclease-mediated metabolism
results in a significantly improved tissue half-life in vivo, resulting
in a longer duration of action and a more intermittent dosing
schedule. Moreover, Gen 2.5-modified ASOs display significantly
superior efficacy in tissues that are less sensitive to earlier gener-
ation ASO chemistries, including tumor cells. In this study, we
show for the first time that systemic administration of an AR-ASO
potently suppressed levels of both AR full-length and AR-Vs and
inhibited AR activity in vivo. An exon-1 targeting AR-ASO inhibited
in vivo growth of ENZ-R LNCaP tumors, with significant knock-
down of AR and AR-V7 expression in vivo, providing preclinical
proof as a promising next-generation anti-AR agent. No AR
knockdown or antitumor activity was observed with multiple control
oligonucleotides.

In summary, these results highlight the AR as an important
driver of ENZ resistance and that while both AR FL and AR-V7
levels are induced, AR FL is an important mediator of ENZ
resistance in the ENZ-R LNCaP model. However, the role of
AR FL and AR-V7 in progression to ENZ-R CRPC appears to be
context-dependent, and therefore, ASO strategies that target
AR FL and AR-Vs is a rational third-line approach for AR pathway
inhibitor-resistant CRPC.

Disclosure of Potential Conflicts of Interest

Y. Loriot is a consultant/advisory board member for Astellas. Y. Kim is an
employee of Isis Pharmaceuticals Inc. No potential conflicts of interest were
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Generation 2.5 Antisense Oligonucleotides Targeting the Androgen Receptor and Its Splice Variants Suppress Enzalutamide-Resistant Prostate Cancer Cell Growth

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