Targeting Fibroblast Growth Factor Receptor Signaling Inhibits Prostate Cancer Progression

Shu Feng1, Longjiang Shao1, Wendong Yu1, Paul Gavine2, and Michael Ittmann1

Abstract

Purpose: Extensive correlative studies in human prostate cancer as well as studies in vitro and in mouse models indicate that fibroblast growth factor receptor (FGFR) signaling plays an important role in prostate cancer progression. In this study, we used a probe compound for an FGFR inhibitor, which potently inhibits FGFR-1–3 and significantly inhibits FGFR-4. The purpose of this study is to determine whether targeting FGFR signaling from all four FGFRs will have in vitro activities consistent with inhibition of tumor progression and will inhibit tumor progression in vivo.

Experimental Design: Effects of AZ8010 on FGFR signaling and invasion were analyzed using immortalized normal prostate epithelial (PNT1a) cells and PNT1a overexpressing FGFR-1 or FGFR-4. The effect of AZ8010 on invasion and proliferation in vitro was also evaluated in prostate cancer cell lines. Finally, the impact of AZ8010 on tumor progression in vivo was evaluated using a VCaP xenograft model.

Results: AZ8010 completely inhibits FGFR-1 and significantly inhibits FGFR-4 signaling at 100 nmol/L, which is an achievable in vivo concentration. This results in marked inhibition of extracellular signal-regulated kinase (ERK) phosphorylation and invasion in PNT1a cells expressing FGFR-1 and FGFR-4 and all prostate cancer cell lines tested. Treatment in vivo completely inhibited VCaP tumor growth and significantly inhibited angiogenesis and proliferation and increased cell death in treated tumors. This was associated with marked inhibition of ERK phosphorylation in treated tumors.

Conclusions: Targeting FGFR signaling is a promising new approach to treating aggressive prostate cancer.

Introduction

Prostate cancer is the most common visceral malignancy and the second leading cause of cancer deaths in men in the United States. There is compelling evidence both from studies of human tumor samples and from animal models that fibroblast growth factors (FGF) and FGF receptors (FGFRs) are important in prostate cancer initiation and progression (reviewed in ref. 1). FGFs are expressed at increased levels in prostate cancer (1, 4, 5, 7-9) and increased expression has been shown to be associated with clinically aggressive disease (7, 10, 11). Recent studies have shown high expression of FGF8 (10) and FGF9 (9) in prostate cancer bone metastases. In all prostate cancer cell lines examined to date one or more FGFs is expressed as an autocrine growth factor (ref. 1; and unpublished data).

Our laboratory has shown that FGFR-1 is expressed in 20% of moderately differentiated cancers and 40% of poorly differentiated localized prostate cancers based on immunohistochemistry (5) and other groups have made similar observations (12, 13). Studies in transgenic mice have linked FGFR-1 activation to cancer initiation and...
Translational Relevance

Prostate cancer is the most common visceral malignancy and the second leading cause of cancer deaths in men in the United States. There is compelling evidence from both studies of human tumor samples and from animal models that fibroblast growth factors (FGF) and FGFRs are important in prostate cancer initiation and progression. In this study, we show that inhibition of FGFR signaling using a novel small-molecule inhibitor inhibits prostate cancer cell invasion in vitro and tumor progression in vivo. These results indicate that targeting FGFR signaling is a promising new therapeutic approach for treating aggressive prostate cancer.

Changes in alternative splicing of FGFR-2 in prostate cancer that enhance oncogenic signaling are well known. It has been shown by several groups (8, 18, 19) including ours (20) that there is a change in alternative splicing favoring expression of the growth-promoting FGFR-2 IIIc isoform with decreased levels of the IIIb isoform but high FGFR-2 protein expression is not strongly linked to prostate cancer progression (21). FGFR-3 appears to play a less important role in prostate cancer based on current data (21).

FGFR-4 is expressed at increased levels in prostate cancer by immunohistochemistry and this has been verified by quantitative reverse transcriptase PCR (RT-PCR; refs. 7, 21–23). Strong FGFR-4 expression is significantly associated with poor clinical outcome (7, 22). For example, Murphy and colleagues (7) have shown that increased FGFR-4 expression is strongly associated with prostate cancer–specific death. Our group has shown that a germline polymorphism in the FGFR-4 gene, resulting in expression of FGFR-4 containing arginine at codon 388 (Arg388), instead of a more common glycine (Gly388), is associated with prostate cancer incidence, recurrence after radical prostatectomy and metastatic disease (23). This allele was present in almost half of white patients with prostate cancer. These findings have been confirmed in a similar case control study (24) and in a meta-analysis of all published studies (25). Expression of the FGFR-4 Arg388 protein results in increased motility and invasion and is associated with prolonged receptor stability after ligand activation (23). In recently published studies, we have shown that FGFR-4 expression leads to increased activity of the extracellular signal–regulated kinase (ERK) pathway, increased activity of serum response factor and activator protein (AP-1), and transcription of multiple genes which are correlated with aggressive clinical behavior in prostate cancer (26). Furthermore, stable knockdown of FGFR-4 via shRNA in PC3 prostate cancer cells (26) resulted in inhibition of proliferation and invasion in vitro and decreased primary tumor growth and metastases in an orthotopic model in which cells are injected directly into the prostates of nude mice. Finally, several groups, including ours, have shown that decreased expression of negative regulators of FGF signaling is common in human prostate cancer and in some cases these alterations have been shown to be associated with aggressive disease (7, 27–31). These negative regulators include the Sprouty proteins as well as Sef. Loss of these negative signaling regulators is an important mechanism of enhancing FGF signaling in prostate cancer. Thus, both correlative studies in human tissues and mouse models strongly support the concept that FGFR signaling plays an important role in prostate cancer.

In prostate cancer, FGF signaling can enhance prostate cancer progression through both by increased proliferation and by preventing cell death (32). FGFRs are well known angiogenic factors and can enhance angiogenesis through paracrine actions on endothelial and other stromal cells in the tumor microenvironment (1). Thus, FGFRs enhance tumor progression via multiple independent mechanisms.

On the basis of the above, FGF signaling is a promising therapeutic target in aggressive prostate cancer. Several “FGF receptor” small-molecule inhibitors have entered clinical trials but many inhibit multiple tyrosine kinases (2). AZ8010 is an ATP-competitive FGFR tyrosine kinase inhibitor. It is chemically related to AZD4547, with similar properties in vitro but has inferior pharmacokinetic properties. Recent studies have shown cellular IC50 values for AZD4547 in Cos-1 cells for FGFR-1, 2, 3, and 4, of 12, 2, 40, and 142 nmol/L, respectively (33) and AZ8010 has similar properties and potently inhibits FGFR-1–3 at less than 100 nmol/L and FGFR-4 at less than 200 nmol/L. The kinase domain of FGFR-4 is divergent from the kinase domains of FGFR-1–3, and many previously tested FGF receptor inhibitors do not effectively target FGFR-4. For example, PD173074, the only other specific small-molecule FGFR inhibitor has a similar IC50 value for FGFR-1–3 but its IC50 value for FGFR-4 is greater than 1,000 nmol/L (34). The only other kinase inhibited at less than 500 nmol/L by AZD4547 was VEGFR2 (IC50: 258 nmol/L in HUVEC cells). A recent report shows potent in vitro and/or in vivo activity of AZD4547 against cell lines from myeloid leukemia, myeloma, and breast cancer (33). We show here that AZ8010 potently inhibits FGF signaling, invasion in vitro, and tumor growth in vivo in prostate cancer cells. These findings support the hypothesis that targeting FGFR signaling is a promising therapeutic approach to treating prostate cancer.

Materials and Methods

Cell lines and tissue culture

Human prostate cancer cells PC3, LNCaP, and PNT1a immortalized normal prostate epithelial cells were maintained in RPMI-1640 medium (Invitrogen) supplemented with 10% FBS (Invitrogen) and 1% penicillin/streptomycin (Invitrogen). VCaP cells were grown in Dulbecco’s Modified Eagle’s Medium under similar conditions. Luciferase-
expressing VCaP cells (VCaP-Luc) for in vivo studies have been described previously (35). PNT1a expressing FGFR-4 Arg188 has been described previously (26) and PNT1a cells overexpressing FGFR-1 were generated in a similar manner by subcloning the FGFR-1 cDNA from clone MGCI11078 into the pCDNA 3.1 vector and then subcloning into the pCDH lentiviral vector. Lentiviruses were generated and used to transduce PNT1a cells that were then selected with puromycin. The expression of FGFR-1 was similar to FGFR-4 Arg188 based on Western blotting with anti-V5 antibodies (26) that detects the V5 tag on both receptors.

Invasion and cell proliferation assays

The Matrigel invasion assays were conducted in triplicate using BD BioCoat Matrigel invasion chambers (BD Biosciences) as described previously (26). Cells were incubated with AZ8010 (100 or 500 nmol/L) or dimethyl sulfoxide (0.1%) vehicle in the presence of FGF2 (50 ng/mL) in serum-free medium or in complete growth medium containing 10% FBS for either 24 (PC3), 48 (PNT1a, PNT1a-FGFR-1, PNT1a-FGFR-4), or 72 hours (LNCaP and VCaP). Noninvasive cells in the upper chambers were removed and the invading cells on the lower surface of the membrane were fixed and stained with Diff-Quik Stain Set (Dade Behring, Inc.). The membranes were mounted on slides and scanned, photographed, and all cells were counted. For cell proliferation analyses, cells were incubated with different concentrations of AZ8010 (0, 100, and 500 nmol/L) for 72 hours in serum-free medium at the presence of FGF2 in 96-well plates. Cell proliferation was determined using the CellTiter 96 Aqueous One Solution Cell Proliferation Assay (Promega) as described by the manufacturer.

Western blotting and immunoprecipitation

Protein extracts were prepared from cells in culture or VCaP xenograft tumors with modified RIPA buffer containing Tris 50 mmol/L, NaCl 150 mmol/L, Triton X-100 1%, SDS 0.1%, deoxycholate 0.5%, 2 mmol/L sodium orthovanadate, 1 mmol/L sodium pyrophosphate, 50 mmol/L NaF, 5 mmol/L EDTA, 1 mmol/L PMSF, and 1× protease inhibitor cocktail (Roach) and clarified by centrifugation. The protein concentrations of the lysates were determined using a bicinchoninic acid protein assay kit (Thermo Scientific). Western blottings were carried out as described previously (26). The antibodies were from Cell Signaling and included phospho-FGFR mouse monoclonal antibody (mAb, #3476; ref. 26), phospho-p44/42 MAPK (p-Erk1/2, #4370), p44/42 MAPK (Erk1/2, #4695), phospho-MEK1/2 (#9154), MEK1/2 (#9122), phospho-AKT (T308, #4056), phospho-AKT (S473, #9271), and β-tubulin (#2128) which were all used at 1:1,000 dilution. β-Actin mAb (Sigma A5316) was used at 1:5,000 dilution. After incubation with primary antibodies for overnight at 4°C, horseradish peroxidase–labeled secondary antibodies were then applied to the membranes for 1 hour at room temperature. Signals were visualized using enhanced chemiluminescence (Thermo Scientific).

To detect phosphorylated FGFR-1 in tumor extracts, immunoprecipitation assays were conducted. Briefly, protein extract (500 µg) of xenograft tumors were precleared by incubating with 1 µg of normal mouse IgG together with 20 µL of resuspended protein A/G Plus-Agarose (Santa Cruz Biotechnology, Inc.) at 4°C for 30 minutes and were subsequently incubated with 2 µg of anti-human FGFR-1 mAb (Meridian Life Science Inc., P55213M) overnight at 4°C. Twenty microliters of resuspended protein A/G Plus-Agarose was then added to the lysate/antibody mixture. Following incubation for 1 hour at 4°C, the lysate/antibody/agarose mixture was centrifuged at 1,000 × g for 5 minutes at 4°C and the pellets were washed 4 times with 1.0 mL of RIPA buffer. Pellets were eluted in 40 µL of electrophoresis sample buffer and analyzed by Western blotting as described earlier with mouse anti-phospho-FGFR mAb (1:1,000; Cell Signaling). Densitometry was carried out using ImageJ program (NIH; Bethesda, MD).

Subcutaneous VCaP xenografts

Thirty nude male mice (6- to 7-week-old) were purchased from Charles River Laboratories International, Inc. and each animal was injected subcutaneously with 1 × 106 VCaP-Luc cells over the flank. Two weeks later, those mice bearing subcutaneous tumors were divided randomly into 2 groups: the experimental group was treated with AZ8010 at 12.5 mg/kg/d in 1% polysorbate 80 by oral gavage; the control group was treated with vehicle only. Luciferase imaging of tumor growth was carried out weekly after injection of r-luciferin using an IVIS imaging system as described previously (35). Body weights were monitored weekly. Four hours after the last treatment, mice were euthanized and tumors were excised and weights and volumes measured. One portion of each tumor was fixed with buffered formalin, embedded in paraffin, and processed for histologic, immunohistochemical, and terminal deoxynucleotidyl transferase–mediated dUTP nick end labeling (TUNEL) analysis; the other portion was snap frozen in liquid nitrogen and proteins extracted. All procedures were approved by the Baylor College of Medicine Institutional Animal Use and Care Committee.

Immunohistochemistry

Immunohistochemistry of mouse tissues was carried out using the basic procedures described previously (28). Primary antibodies were used as follows: Ki67 (Thermo Scientific, RM-9106) at 1:400 for 30 minutes at room temperature and mouse anti-CD31 (BD Biosciences) at 1:10 overnight at 4°C plus 3 hours at room temperature. TUNEL was conducted using an ApopTag Peroxidase In Situ Apoptosis Kit (Millipore) according to the manufacturer’s instructions. Image analysis of stained sections was conducted as described previously (36). Ki-67 and TUNEL were also carried out on cells grown on chamber slides and quantitated in a similar manner.

Quantitative RT-PCR

Copy numbers of all 4 FGFRs in prostate and prostate cancer cell line RNAs was determined using quantitative RT-PCR using general procedures described previously (37).
Primers and PCR conditions for FGFR-4 have been described. Primers and conditions for FGFR-1–3 are shown in Supplementary Table S1. In all cases exact copy number was determined in duplicate samples using a standard curve generated using purified PCR product cloned into plasmid or full-length cDNA. Hypoxanthine phosphoribosyltransferase (HPRT) levels were determined as described previously (6) and used to normalize expression levels across cell lines.

Results
Expression levels of FGFRs in prostate and prostate cancer cell lines
To better understand the impact of FGFR inhibition on prostate cancer cell lines, we first sought to determine the relative expression of all 4 FGFR mRNAs in the immortalized prostate epithelial cell line PNT1a and the commonly used prostate cancer cell lines PC3, LNCaP, VCaP, and DU145 (Fig. 1). All cell lines expressed detectable levels of all 4 FGFRs. FGFR-2 was expressed at relatively low levels in all cell lines compared with other FGFRs. FGFR-1 and FGFR-3 were expressed at similar levels whereas FGFR-4 was expressed at the highest level overall. Unfortunately, the absence of high quality, specific antibodies with similar affinities for all 4 FGFRs precludes confirmation at the protein level. Our data indicates that there is ubiquitous expression of FGFRs in prostate cancer, with significant but variable expression of FGFR-4.

AZ8010 inhibits FGFR signaling in vitro
PNT1a are immortalized normal prostatic epithelial cells and when expressing exogenous FGFR most FGFR signaling can be attributed to the transfected receptor due to its high expression under a relatively strong promoter (37). We have previously established a cell line overexpressing FGFR-4 Arg388, and these cells express 90-fold higher levels of FGFR-4 than the parental PNT1a by quantitative RT-PCR (37). We have now established similar cell line expressing FGFR-1 which expresses FGFR-1 at similar levels to FGFR-4 in the FGFR-4–overexpressing cells (data not shown). In these cells, 100 nmol/L AZ8010 inhibits FGFR-1 phosphorylation by 86% by quantitative Western blotting at 4 hours after treatment in serum-free medium with FGF2 as the only growth factor (Fig. 2A). This is equivalent to the 86% inhibition of FGFR-1 phosphorylation seen at 1,000 nmol/L AZ8010. ERK phosphorylation was also markedly inhibited (by 78% and 84%) at 100 and 1,000 nmol/L, respectively. In PNT1a cells overexpressing FGFR-4, phosphorylation was very significantly inhibited at 100 nmol/L (73% by quantitative densitometry) although inhibition was somewhat less than that seen at 500 nmol/L, which inhibits 89% of FGFR-4 phosphorylation (Fig. 2B). More residual ERK phosphorylation seen in FGFR-4 expressing cells at 100 nmol/L AZ8010 (55% inhibition) and 200 nmol/L AZ8010 (70% inhibition) when compared with the
90% inhibition at 500 nmol/L AZ8010 by quantitative analysis of normalized band intensities. The FGFR-4 studies used 24-hour treatment as we have shown that FGFR-4 Arg^{188} phosphorylation can be sustained for up to 24 hours after ligand stimulation (37). Control PNT1a cells also showed marked inhibition of ERK phosphorylation at both 100 and 500 nmol/L AZ8010. Note that while PNT1a express FGFR-1, FGFR-3, and FGFR-4, phosphorylated FGFRs cannot be detected by simple Western blotting in these cells, unlike the FGFR-1 and FGFR-4 transfected cells, confirming marked overexpression of the transfected receptor protein in the latter cell lines. Thus, at 100 nmol/L AZ8010 FGFR-1 is markedly inhibited and FGFR-4 is significantly but not totally inhibited.

AZ8010 inhibits invasion in vitro

We next examined the impact of AZ8010 on invasion using these same 2 PNT1a-derived cell lines and the PNT1a control cells in defined medium with FGF2 as the only growth factor as we have previously shown that ERK-dependent invasion is a major phenotype driven by FGFR-4 in prostate cancer cells. In these experiments, we used 500 nmol/L AZ8010 to maximally suppress either FGFR-1 or FGFR-4 activity. AZ8010 markedly inhibited invasion (Fig. 3) in both FGFR-4 (67%, \(P = 0.04, t \text{-test} \)) and FGFR-1 (68%, \(P = 0.02 \)) expressing cells. Invasion of control PNT1a cells, which showed lower numbers of invasive cells, was also potently inhibited (63%, \(P = 0.01 \)) so that the effects seen in the overexpressing cell lines are probably partly due to inhibition of endogenous FGFRs and partially due to inhibition of the overexpressed FGFR. Thus AZ8010 can potentially inhibit invasion of immortalized prostate epithelial cells and cells overexpressing either FGFR-1 or FGFR-4.

We then evaluated the impact of AZ8010 on prostate cancer cell invasion in defined medium with FGF2 as the only growth factor (Fig. 4A) and in serum-containing
medium (Fig. 4B). For both LNCaP and PC3 cells invasion in FGF2-defined medium was markedly reduced by 100 nmol/L AZ8010 (LNCaP, 78%; PC3, 56%, both P < 0.01, t test). Thus, in the face of saturating quantities of FGF2, the majority of invasion can be accounted for by FGFR signaling. Results with 500 nmol/L AZ8010 were essentially the same as with 100 nmol/L. Somewhat surprisingly invasion was markedly inhibited in serum-containing medium by 45% to 62% in LNCaP, PC3 and VCaP cell lines at 100 nmol/L AZ8010 (all P < 0.01, t test). This result indicates that FGFs in serum and/or autocrine FGFs from cancer cells drive a significant fraction of invasion by prostate cancer cells, even in serum, which contains other growth factors. Treatment with 500 nmol/L AZ8010 further decreased invasion somewhat compared 100 nmol/L AZ8010 but the differences were not statistically significant.

Proliferation was decreased in FGF2-defined medium (Fig. 4C) at both 100 and 500 nmol/L AZ8010 but effects on proliferation were less pronounced than those on invasion (11%–38% inhibition of proliferation). Analysis of AZ8010-treated VCaP cells with Ki67 immunohistochemistry and TUNEL showed statistically significant decreases in Ki67 staining and increases in TUNEL at both doses (Supplementary Fig. S1). Similar results were seen with PC3 and LNCaP cells (data not shown). No statistically significant effect on proliferation was seen on prostate cancer cell lines in serum-containing medium (data not shown). Of note, PC3 which express higher levels of FGFR-4 than VCaP (Fig. 1), showed similar responses to both 100 and 500 nmol/L AZ8010, indicating that higher FGFR-4 expression does not contribute significantly to resistance to AZ8010 at these levels of drug.

AZ8010 inhibits tumor growth in vivo

We then tested the antitumor activity of the AZ8010 using VCaP cells expressing luciferase in vivo. Two weeks after subcutaneous injection in nude mice, animals were treated with AZ8010 at 12.5 mg/kg/d by oral gavage or vehicle only. Tumors were collected 4 hours after the last drug treatment. As seen in Fig. 5A, this treatment resulted in nearly complete inhibition of tumor growth by luciferase imaging. Mean tumor weight after 4 weeks of treatment was significantly decreased (Fig. 5B): 194 mg for treated tumors versus 910 mg for controls, (P = 0.01, Mann–Whitney). No toxicity was detected and mouse weights were stable throughout this experiment and no differences were seen in body weight between the treated and control groups (Fig. 5B). Tumor sections were then analyzed using immunohistochemistry for Ki67 to evaluate proliferation and CD31 to evaluate angiogenesis. Apoptosis was evaluated by TUNEL and all 3 markers were quantitated using image analysis (Fig. 5C). Ki67 staining was decreased by 22% (P < 0.01, Mann–Whitney) whereas TUNEL was increased by almost 250% (P < 0.02, Mann–Whitney). Blood vessel area as determined by CD31 immunostaining and image analysis was decreased by 58% (P < 0.001, Mann–Whitney). See Supplementary Fig. S2 for representative images of stained slides. These findings are concordant with the decreased tumor growth observed.

Figure 5. AZ8010 treatment inhibits tumor progression in vivo. A, nude mice were injected subcutaneously with VCaP-expressing luciferase. After 2 weeks (0 time point), luciferase flux in tumors was measured using a Xenogen imager after luciferin injection. Mice were then treated by oral gavage with 12.5 mg/kg/d AZ8010 or vehicle and tumor luciferase flux measured weekly for 4 weeks. Values are mean ± SEM (n = 21, treated; n = 24, control). B, left, mean tumor weights ± SEM in AZ8010 treated and control mice at termination of treatment. Values expressed as percentage of tumor size of control mice; right, mean body weights (± SEM) of mice treated with AZ8010 or vehicle at the initiation and termination of treatment. Values expressed as percentage of weight of control mice at the initiation of treatment. C, mean percent nuclei stained with Ki67 or TUNEL or mean tumor area stained with CD31 in treated and control tumors. Values expressed as percentage of control ± SEM. *, P < 0.05; **, P < 0.01; ***, P < 0.001.
In vivo targets of AZ8010

To evaluate inhibition of activation of key signaling targets by AZ8010 in vivo, protein lysates of VCaP xenografts treated with AZ8010 or controls were analyzed. Equal quantities of xenograft extract protein were immunoprecipitated with anti-FGFR-1 and immunoblotted with anti-phospho-FGFR antibodies. Phosphorylated FGFR-1 was markedly decreased (Fig. 6A) and quantitative analysis of Western blotting showed a 95% decrease in band intensity relative to controls ($P < 0.04$, $t$ test). Western blotting of tumor extracts were also analyzed for alterations of MAP–ERK kinase (MEK) phosphorylation (Fig. 6B), which is upstream of ERK. MEK phosphorylation was visibly decreased and by quantitative analysis of Western blotting there was a 56% decrease in band intensity relative to controls ($P < 0.01$, $t$ test). ERK phosphorylation (Fig. 6C) was also significantly inhibited and, by quantitative analysis, band intensity was decreased by 84% ($P < 0.02$, $t$ test). Thus, the predicted targets show significant inhibition in vivo in tumors treated with AZ8010. Interestingly, we saw no alteration in AKT phosphorylation in treated tumors (Fig. 6D), although in some systems AKT activation is downstream of FGFR signaling. Concordant with this observation, we observed no decrease in AKT activation upon treatment with AZ8010 in PC3 and FGFR-4 expressing PNT1a cells (Supplementary Fig. S3). Thus ERK, rather than AKT, seems to be the critical target of AZ8010 in vivo.

Discussion

On the basis of correlative studies in human tissue samples and animal model studies, FGFR signaling is a promising therapeutic target in prostate cancer. Our studies with AZ8010 support this concept. It should be noted that reported analyses to date do not show high level amplification or point mutations of FGFRs in prostate cancer tissues, in contrast to the findings in other malignancies such as gastric cancer (amplification) or bladder cancer (point mutation). In prostate cancer, there is overexpression of multiple FGF ligands, increased receptor expression, association of progression with germline polymorphisms that enhance signaling, and downregulation of FGF signaling inhibitors (2). Thus, while somatic DNA structural alterations are reliable indicators of susceptibility to targeted agents in many cases, other alterations can also be indicative of involvement of a specific signaling pathway in cancer progression.

One interesting aspect of our in vitro studies is our finding that the FGFR inhibitor had significant effects on invasion in all cell lines tested while effects on proliferation were significantly weaker. However, net cell growth in vivo was markedly inhibited by FGFR inhibition. It is interesting to note that the TMPRSS2/ERG fusion gene, which is present in 40% to 60% of human prostate cancers, strongly promotes invasion in vitro but has more limited affects on proliferation in vitro and yet when it is knocked down with shRNA, tumor progression in vivo is significantly inhibited (35). One interpretation of these findings is that invasive capacity is required for tumor growth in vivo and that effects on proliferation in vitro may not necessarily reflect the ability of a drug or knockdown of a gene target to inhibit tumor progression in vivo.

In addition to direct effects on tumor invasion in prostate cancer, inhibition of FGFR signaling has significant effects on the tumor microenvironment, either directly or indirectly. One major target is angiogenesis, which was decreased by almost 60% in treated tumors. This may reflect the well known direct affects of FGF signaling on endothelial cells and other vascular cells to promote angiogenesis (2). In addition, there may be indirect effects on tumor cells...
of FGFR inhibition that could inhibit secretion of paracrine factors that promote angiogenesis. For example, VEGF has been shown to be induced by FGFR signaling in some systems (38). Similarly, FGFR signaling also plays a role in myofibroblast promotion of prostate cancer progression, in part by enhancing angiogenesis (39). It is likely that the decreased proliferation and increased cell death seen in the treated tumors in vivo is in part due to inhibition of angiogenesis and other microenvironmental effects and this accounts for some of the difference between in vitro and the in vivo affects on net proliferation. It is also possible that these effects may be due to changes in the biology of the cancer cells themselves when growing in an in vivo context. One potential explanation is that in tumors the effective FGF concentration is higher due to binding of secreted FGFs by extracellular matrix proteins within the tumor. Further studies are needed to understand in detail the importance of different activities in the observed tumor growth inhibition.

As noted earlier, AZ8010 inhibits VEGFR2 activation at an IC_{50} value of greater than 200 nmol/L. VEGFR2 is expressed on endothelial cells and promotes angiogenesis (40) so that it is possible that some of the effects seen on angiogenesis are a result of inhibition of endothelial VEGFR2. However, 2 hours after oral administration of AZ8010 in nude mice free serum levels of the drug are approximately 170 and 64 nmol/L by 4 hours, with levels following to 3 nmol/L at 24 hours after treatment (unpublished data). Thus, any inhibition of endothelial VEGFR2 (and VEGFR2 on prostate cancer cells) is likely to be quite transient using a daily drug administration. Thus, while inhibition of endothelial VEGFR2 may play a role in the effects seen in vivo, it is likely to be minor. Overall, it is likely that the vast majority of the antitumor effects of AZD81010 in vivo can be accounted for by FGFR inhibition but further studies are needed to clarify this point. Of course, from a clinical point of view, some VEGFR2 inhibition is not a negative attribute for a cancer therapeutic.

We have previously shown that ERK activation is a major downstream target of activated FGFRs and ERK activation strongly promotes prostate cancer cell invasion in vitro (26). A striking result of our studies is that the vast majority of ERK activation in VCaP cells in vivo (>80%) can be attributed to FGFR activation. The extent of this inhibition is surprising given that many growth factor receptors can activate ERK. However, this finding implies that FGFRs are the major growth factor receptor ligands in VCaP cells that activate ERK in vivo. This is clinically relevant as our previous studies have shown that an ERK driven gene signature is associated with aggressive disease in prostate cancer (26). Equally striking was the lack of effect on AKT activation. To date, we have not seen major direct effects of FGFR signaling on AKT activation in prostate cancer cell lines, even in cells with PTEN inactivation (unpublished data). Of note, studies with AZD4547 show variable impact of FGFR inhibition on AKT activation, with breast cancer cell lines showing inhibition of AKT activation whereas myeloma and myeloid leukemia cells did not show any effect (33). Thus, FGFR activation of AKT seems to be highly context dependent. This implies that in prostate cancer FGFR inhibition and targeted inhibition of the AKT pathway may be a rationale therapeutic strategy in cancer subtypes not showing inhibition of AKT activation by FGFR inhibitors. The extent to which other signaling pathways activated by FGFRs, such as PLC-γ and STATs (1–3), contribute to the antitumor efficacy of FGFR inhibition in prostate cancer in vivo will need to be determined.

AZ8010 is highly chemically related to a newer generation FGFR inhibitor AZD4547 (33), and its properties in vitro are almost identical to AZD4547, but it has inferior pharmacokinetic properties. As described earlier, 2 hours after administration of AZ8010 serum levels are approximately 170 nmol/L and falls to 3 nmol/L by 24 hours after administration. Thus, effective drug concentrations that can inhibit FGFR-4, and to a lesser extent FGFR-1, are not maintained for the entire 24 hours between drug administrations in our studies. This almost certainly decreases its potential efficacy and it is likely that AZD4547 will be more potent in vivo in targeting prostate cancer expressing higher levels of FGFR-4. AZD4547 is currently undergoing phase I clinical trials in patients with advanced cancers. Our studies suggest that the AZD4547 may be useful in the treatment of aggressive prostate cancer at various clinical stages.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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