Nonclinical Antiangiogenesis and Antitumor Activities of Axitinib (AG-013736), an Oral, Potent, and Selective Inhibitor of Vascular Endothelial Growth Factor Receptor Tyrosine Kinases 1, 2, 3

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Abstract

Purpose: Axitinib (AG-013736) is a potent and selective inhibitor of vascular endothelial growth factor (VEGF) receptor tyrosine kinases 1 to 3 that is in clinical development for the treatment of solid tumors. We provide a comprehensive description of its in vitro characteristics and activities, in vivo antiangiogenesis, and antitumor efficacy and translational pharmacology data.

Experimental Design: The potency, kinase selectivity, pharmacologic activity, and antitumor efficacy of axitinib were assessed in various nonclinical models.

Results: Axitinib inhibits cellular autophosphorylation of VEGF receptors (VEGFR) with picomolar IC_{50} values. Counterscreening across multiple kinase and protein panels shows it is selective for VEGFRs. Axitinib blocks VEGF-mediated endothelial cell survival, tube formation, and downstream signaling through endothelial nitric oxide synthase, Akt and extracellular signal-regulated kinase. Following twice daily oral administration, axitinib produces consistent and dose-dependent antitumor efficacy that is associated with blocking VEGFR-2 phosphorylation, vascular permeability, angiogenesis, and concomitant induction of tumor cell apoptosis. Axitinib in combination with chemotherapeutic or targeted agents enhances antitumor efficacy in many tumor models compared with single agent alone. Dose scheduling studies in a human pancreatic tumor xenograft model show that simultaneous administration of axitinib and gemcitabine without prolonged dose interruption or truncation of axitinib produces the greatest antitumor efficacy. The efficacious drug concentrations predicted in nonclinical studies are consistent with the range achieved in the clinic. Although axitinib inhibits platelet-derived growth factor receptors and KIT with nanomolar in vitro potencies, based on pharmacokinetic/pharmacodynamic analysis, axitinib acts primarily as a VEGFR tyrosine kinase inhibitor at the current clinical exposure.

Conclusions: The selectivity, potency for VEGFRs, and robust nonclinical activity may afford broad opportunities for axitinib to improve cancer therapy.

The vascular endothelial growth factor (VEGF)/VEGF receptor tyrosine kinase (RTK) signaling pathway plays a pivotal role in tumor angiogenesis by promoting vascular and lymphatic endothelial cell proliferation, survival, and invasion, resulting in neovascularization, tumor growth, and metastasis (1–4). Many antiangiogenic agents including multi-RTK inhibitors (RTKI) are either approved or are being tested in clinical trials. Sunitinib [anti-VEGF, platelet-derived growth factor receptors (PDGFR), KIT, and Flt-3] is Food and Drug Administration approved for the treatment of advanced renal cell carcinoma (5) and imatinib-refractory gastrointestinal stromal tumors (6) and is in phase III development across multiple tumor types. Sorafenib (anti-VEGFR, PDGFR, b-Raf, Flt-3, and KIT) is approved for the treatment of advanced metastatic renal cell carcinoma (7) and for the first-line treatment of advanced hepatocellular carcinoma, whereas it had limited activity in advanced non-small cell lung cancer (8). In addition, bevacizumab (anti-VEGF-A monoclonal antibody) is approved for the treatment of first-line colorectal cancer in combination with 5-fluorouracil-based regimens (9), for subgroups of advanced non-small cell lung cancer in combination with paclitaxel/carboplatin (10), and recently for late-stage breast cancer in combination with Taxol (11). Several other RTKIs with varying...
Axitinib is an oral, potent, and selective VEGFR inhibitor currently in phase II/III development. Clinical reports and narrowly focused academic publications have been published. There is a need to describe the characteristics of axitinib based on information of discovery and translational research. Clinical Cancer Research is an ideal journal for this article because its broad audience of medical oncologists, translational researchers, and basic research scientists can all benefit from this comprehensive and integrated report. The translational value of the article includes the clinically relevant target and efficacious concentrations; the nature of axitinib’s selectivity in the context of the current clinical dose; the molecular basis for clinical hypertension and why it would be manageable; the potential impact of dose scheduling, interruption, or truncation on antitumor efficacy; and for the first time the proof of concept of enhanced benefit by targeting both the VEGF ligand and intracellular VEGFR of tumor vasculature—a hypothesis that is being tested in the clinic. We also briefly discuss the difference in selectivity profile between several similar RTKIs, an issue of interest in the field of antiangiogenesis. This discussion provides clarification on why we believe axitinib would present non-overlapping and important therapeutic opportunities in the clinic.

**Materials and Methods**

**Compounds synthesis and formulation**

Axitinib (N-methyl-2-[3(E)-2-pyridin-2-yl- vinyl-1H-indazol-6-ylsulfonyl]benzamide) was synthesized as described in U.S. Patent 6,534,524. For in vitro experiments, axitinib was dissolved in 10 mmol/L DMSO and diluted as needed, and for in vivo studies, axitinib was formulated in 0.5% carboxymethylcellulose/H2O/HCl (g/v, pH 2-3) and dosed as a suspension at 5 mL/kg orally twice daily. Bevacizumab (Avastin; Henley Shein) was formulated in sterile PBS and dosed at 5 mg/kg i.v. twice a week, Docetaxel (Taxotere; Amersham/Bergen Brunswik) was administered i.v. at 5 to 40 mg/kg once a week. Carboplatin was dosed i.p. daily for 5 days during each treatment cycle. Gemicitabine (Eli Lilly) was formulated in 0.9% NaCl and dosed i.p. 3 times per d for 4 d with a 10-day dosing break between cycles.

**Cells and cell culture**

Human umbilical vein endothelial cells (HUVEC) were purchased from Clonetics or Cambrex Bio Science. Human microvascular endothelial cells were purchased from Cascade Biologics. MV522 (human colon cancer) cells were obtained from the University of California. M24met (human melanoma) cells were provided by Dr. Barbara Mueller (La Jolla Institute for Molecular Medicine). Tumor cell lines LLC (murine Lewis lung carcinoma), NIH-3T3 (murine fibroblastoma), C6 (rat glioblastoma), U87MG (human glioblastoma), MDA-MB-231 (human breast carcinoma), HT29 (human colon carcinoma), A375 and A2058 (human melanoma), NCI-H526 (human small cell lung carcinoma), A2780 (human ovarian carcinoma), and Namalwa (human lymphoma) were obtained from the American Type Culture Collection.

**Animals**

Female mu/mu mice or severe combined immunodeficient beige mice (ages 7-10 weeks) were obtained from Harlan or Charles River Laboratories. Animals were fed Lab Diet 5061 (PM Nutrition International) and water ad libitum. Animal experiments were carried out in accordance with the Guide for the Care and Use of Laboratory Animals (NIH, 1996) by Institute of Laboratory Animal Research (NIA).

**Cellular receptor kinase phosphorylation assay**

Porcine aorta endothelial (PAE) cells overexpressing full-length VEGFR-2, PDGFR-β, KIT, and NIH-3T3 overexpressing murine VEGFR-2 (Flk-1) or PDGFR-α were generated as described previously (27, 28). The ELISA capture plates were prepared by coating 96-well ReactiBlind plates (Pierce) with 100 μL/well of 2.5 μg/mL anti-VEGFR-2 antibody (Novus Biologicals), 0.75 μg/mL anti-PDGFR-β antibody, 0.25 μg/mL anti-PDGFR-α antibody (both Santa Cruz Biotechnology), 0.5 μg/mL anti-KIT antibody (NeoMarkers), or 1.20 μg/mL anti-Flk-1 antibody (Invitrogen). Measurement of RTK phosphorylation by ELISA was done as described previously (29).

**Three-dimensional spheroidal tube formation assay**

Five hundred human microvascular endothelial cells were added to ECM-2 medium containing 0.24% methylcellulose and transferred to U-bottomed 96-well plates to form a spheroid overnight. Approximately 50 spheroids were collected and mixed with 2 mg/mL fibrinogen solution containing 4% to 8% fetal bovine serum (FBS).
with or without compound in the 48-well plates coated with thrombin (5,000 units/mL). The resulting three-dimensional fibrin gel was covered with EGM-2 containing 4% to 8% FBS and incubated at 37°C. Endothelial tube formation was observed daily under an inverted microscope.

**Immunoprecipitation and immunoblotting**

Endothelial or tumor cells were starved for 18 h in the presence of either 1% FBS (HUVEC) or 0.1% FBS (tumor cells). Axitinib was added and cells were incubated for 45 min at 37°C in the presence of 1 mmol/L Na3VO4. The appropriate growth factor was added to the cells, and after 5 min, cells were rinsed with cold PBS and lysed in the lysis buffer (Cell Signaling) and a protease inhibitor cocktail (Roche Applied Science). The lysates were incubated with immunoprecipitation antibodies for the intended proteins overnight at 4°C. Antibody complexes were conjugated to protein A beads and supernatants were separated by SDS-PAGE. The Super Signal West Dura kit (Pierce) was used to detect the chemiluminescent signal.

**In vivo target modulation**

**VEGFR-2 phosphorylation inhibition in the rat development model.** Six-day-old Sprague-Dawley rats (Charles River Laboratory) were given two i.p. injections of axitinib. Animals were sacrificed, retinas were collected and lysed, and immunoprecipitation/immunoblotting experiments were done as described above. ECL-Plus (Amersham Pharmacia Biotech) was used for detection and densitometry analysis was done using the Alpha Imager 8800 (Alpha Innotech). VEGFR-2 phosphorylation inhibition in xenograft tumors. Mice with M24met xenograft tumors (400-600 mm3) were administered with a single i.p. injection of axitinib with or without compound in the 48-well plates coated with thrombin (5,000 units/mL). The resulting three-dimensional fibrin gel was covered with EGM-2 containing 4% to 8% FBS and incubated at 37°C. Endothelial tube formation was observed daily under an inverted microscope.

**Axitinib pharmacokinetics**

Plasma concentrations of axitinib were quantitatively determined by a triple-quadrupole mass spectrometer equipped with a high-performance liquid chromatography system (Agilent 1100) using a Phenyl column (Zorbax Eclipse XDB, 5 μm particle size, 50 × 2.1 mm) under isotropic conditions of 60:40 water/acetonitrile containing 0.1% formic acid. Data were collected under multiple reaction monitoring mode of m/z 387.3—356.2 for axitinib and m/z 394.2—360.2 for the internal standard, AG-013736-d7. The method quantified for axitinib over the range of 1 to 1,000 ng/mL in mouse plasma. The area under the plasma concentration-time curve of axitinib was calculated using the linear trapezoidal rule.

**Skin vascular permeability assay in naïve or tumor-bearing mice**

The assay was done according to Miles and Miles (30) with some modifications. nu/nu mice (n = 5-8) received a single oral dose of axitinib followed by an injection of 30 μL Evan’s blue dye through the tail vein. Thirty minutes later, murine VEGF-A (400 ng in 10 μL PBS) or PBS was injected into the trunk area posterior to the shoulder of the animal. Four hours later, the skin region immediately surrounding the blue color area was dissected and immersed in 1 mL formamide. Evan’s blue was extracted by incubating the tissues in formamide at 56°C for 24 h. Vascular permeability was quantified by measuring light absorbance at 620 nm.

**Mouse xenograft models**

In general, tumor cells in FBS-depleted medium were implanted s.c. into the right flank region of athymic mice, except for the following: the M24met cells were implanted intradermally in a 50 to 100 μL volume in BALB/C severe combined immunodeficient mice; the procedures for orthotopic implantation of HCT-116-GFP and SN12C-GFP tumors have been described elsewhere (31); the A375 cells were implanted in the presence of 10% Matrigel; the LLC tumors were inoculated either using the suspension cells or 2 × 2 mm viable tumor fragments via the Trocar needles. Unless otherwise specified, mice were randomized when the average tumor was ~ 100 mm3 (9-12 per group). Tumor volumes
were measured three times per week by electronic calipers and calculated according to the following equation: 0.5 \times [\text{length} \times \text{width}^2]$. Treatment usually lasted for 2 to 4 weeks or until tumors reached 1,500 mm$^3$. The procedure for tumor bioluminescent imaging and quantification using the IVIS Imaging System (Xenogen) has been reported elsewhere (32).

**Results**

**Axitinib potently inhibits cellular VEGF RTK activities in vitro.** In transfected or endogenous RTK-expressing cells, axitinib potently blocked growth factor-stimulated phosphorylation of VEGF-2 and VEGF-3 with average IC$_{50}$ values of 0.2 and 0.1 nmol/L, respectively (Table 1). Cellular activity against VEGF-1 was 1.2 nmol/L (measured in the presence of 5 nmol/L; Table 1); IC$_{50}$ against murine VEGFR-2 (Flk-1) in Flk-1-transfected NIH-3T3 cells was 0.18 nmol/L, similar to that of its human homologue. Axitinib showed 8- to 25-fold higher IC$_{50}$ against the closely related type III and V family RTKs, including PDGFR-β (1.6 nmol/L), KIT (1.7 nmol/L), and PDGFR-α (5 nmol/L; Table 1); nanomolar concentrations of axitinib blocked PDGF BB-mediated human glioma U87MG cell (PDGFR-β-positive) migration but not proliferation (data not shown). In contrast,
Table 1. Enzymatic $K_i$ and cellular IC$_{50}$ values determined by receptor phosphorylation assays

<table>
<thead>
<tr>
<th>Target</th>
<th>ELISA* RTK phosphorylation, IC$_{50}$ (nmol/L) ± SD</th>
<th>Immunoprecipitation/immunoblotting $^\dagger$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEGFR-2 (KDR)</td>
<td>$0.20 \pm 0.06$ (VEGFR-2/PAE)</td>
<td>0.06 (HUVEC)</td>
</tr>
<tr>
<td>VEGFR-1 (Flt-1)</td>
<td>N.D.</td>
<td>$-0.1 \dagger$ (HUVEC)</td>
</tr>
<tr>
<td>Murine VEGFR-2 (Flk-1)</td>
<td>$0.18 \pm 0.03$ (Flk-1/NIH-3T3)</td>
<td>N.D.</td>
</tr>
<tr>
<td>VEGFR-3</td>
<td>N.D.</td>
<td>0.1–0.3 (VEGFR-3/PAE)</td>
</tr>
<tr>
<td>PDGFR-β</td>
<td>$1.6 \pm 0.4$ (PDGFR-β/PAE)</td>
<td>2.9 $^\dagger$ (NIH-3T3)</td>
</tr>
<tr>
<td>PDGFR-α</td>
<td>$5.0 \pm 1.0$ (PDGFR-α/NIH-3T3)</td>
<td>N.D.</td>
</tr>
<tr>
<td>KIT</td>
<td>$1.7 \pm 0.6$ (KIT/PAE)</td>
<td>0.98 $^\dagger$ (NCI-H526)</td>
</tr>
<tr>
<td>CSF-1R</td>
<td>$73 \pm 18$ (CSF-1R/NIH-3T3)</td>
<td>N.D.</td>
</tr>
<tr>
<td>Flt-3</td>
<td>&gt;1,000 (RS;411)</td>
<td>N.D.</td>
</tr>
</tbody>
</table>

*Abbreviation: N.D., not determined.

$\dagger$ Measured in the presence of 0.1% FBS.

$^\dagger$ Measured in the presence of 1% FBS (HUVEC) or 0.1% FBS (PAE or tumor cells).

Axitinib had much weaker target and functional activity against FGFR-1 (Fig. 1A and B; Table 1). With up to 1 μmol/L concentrations, axitinib showed minimal activity against Flt-3 in RS;411 cells and RET in TT cells (data not shown). A similar trend was observed for enzymatic inhibitory activity ($K_i$) against recombinant tyrosine kinases of the aforementioned receptors (data not shown). Importantly, axitinib had little inhibition against “off-target” protein kinases; at a concentration of 1 μmol/L (∼1,000-fold of the $K_i$ for VEGFR-2) across three kinase panels of ∼100 protein kinases (Pfizer in-house; Upstate and Dundee panels), axitinib inhibited only five protein kinases: Abl, Aurora-2, Arg, AMPK, Axl, and MST2 (∼60% inhibition). Finally, axitinib exhibited no significant activity in a broad protein kinase screen (Cerep; data not shown).

Axitinib inhibits VEGF-mediated endothelial cell survival, migration, and tube formation. Axitinib showed potent inhibition of VEGF-stimulated but not basic FGF-stimulated HUVEC survival with ∼1,000-fold selectivity for VEGFR-2 versus FGFR-1 receptors (Fig. 2B). The average IC$_{50}$ value for VEGFR-2 derived from the functional assays (0.24 ± 0.09 nmol/L) was similar to that obtained in the cellular receptor phosphorylation assays (Table 1), confirming that receptor antagonism led to a functional inhibition by the compound. In addition, axitinib dose-dependently inhibited spheroidal endothelial tube formation in a three-dimensional fibrin matrix system (Fig. 2C; Supplementary Fig. S1). Higher compound concentrations than other types of assays were required to inhibit tube formation because of the presence of the higher serum level (4–8% FBS) in the system.

Axitinib inhibits intracellular signal transduction in endothelial cells. Axitinib rapidly and dose-dependently reduced the phosphorylation of Akt, endothelial nitric oxide synthase (eNOS), and extracellular signal-regulated kinase 1/2 (ERK1/2), key downstream signaling molecules of VEGF (Fig. 2D), with IC$_{50}$ values similar to that of the inhibition of VEGFR-2. This suggests that the reduction in Akt, eNOS, and ERK1/2 phosphorylation may be due to antagonism of upstream VEGFRs by axitinib.

Target modulation in vivo by axitinib. Acute axitinib treatment rapidly and significantly reduced retinal vascular VEGF-2 phosphorylation. One hour after the second dose, retinal VEGF-2 phosphorylation was reduced by 80% to 90% compared with that of the control tissues (Fig. 3A, left). Six and 24 to 32 h post-dose, the phospho-VEGFR-2 levels returned to ∼50% and 100% of the control, respectively. Levels of phospho-VEGFR-2 inversely correlated with axitinib plasma concentrations over the study time course. The EC$_{50}$ value for the inhibition of VEGFR-2 phosphorylation was 0.49 nmol/L (or 0.19 ng/mL, the unbound value corrected for plasma protein binding; Fig. 3A, right).

Axitinib also inhibited murine VEGFR-2 phosphorylation in angiogenic vessels of xenograft tumors of the M24met; M24met tumors secrete high VEGF-A, are highly vascularized, and do not express functional human VEGFR-2. A single oral dose of axitinib (100 mg/kg) markedly suppressed murine VEGFR-2 phosphorylation for up to 7 h compared with control tumors (Fig. 3B). Phosphorylation of downstream ERK1/2 was also measured from the same samples. Compared with the control, partial inhibition of ERK1/2 signal was observed in treated tissues as early as 30 min post-dose and remained inhibited for at least 7 h (Fig. 3C).

Axitinib rapidly inhibited VEGF-induced vascular permeability in the skin of mice; the inhibition was dose-dependent and directly correlated with drug concentration in mice (Fig. 3D). Pharmacokinetic/pharmacodynamic analysis indicated an unbound EC$_{50}$ of 0.46 nmol/L (Supplementary Fig. S2). Similar inhibitory effects were also shown in the skin of MV522 tumor-bearing mice without exogenous VEGF-A stimulation (data not shown).

Taken together, the required in vivo pharmacologic concentration ($C_{target}$) based on the inhibition of vascular VEGFR-2 phosphorylation and VEGF-mediated permeability is ∼0.5 nmol/L (unbound), which translates to a $C_{target}$ of ∼100 nmol/L (or 40 ng/mL, total concentration) in humans.

Axitinib inhibits tumor growth and angiogenesis in mice. Axitinib inhibited the growth of human xenograft tumors in mice (Table 2). Axitinib produced dose-dependent growth delay regardless of initial tumor size, model type, or implant site. Importantly, axitinib exhibited primary tumor inhibition and distant metastasis control in orthotopically implanted tumors such as M24met (melanoma), HCT-116 (colorectal cancer), and SN12C (renal cell carcinoma). A dose-dependent...
growth inhibition in the MV522 tumor model is shown (Fig. 4A). Tumor growth inhibition (TGI) was associated with central necrosis, reduction in microvessel density (CD31 staining) and Ki-67, and increased caspase-3 in the tumor (Fig. 4B; Supplementary Fig. S3). Similar effects were observed in all tumor types examined regardless of tumor type and RTK expression. In summary, axitinib treatment produced consistent antitumor efficacy across various tumor types and this activity is associated with reduction in vascular angiogenesis and tumor proliferation and increase in tumor apoptosis.

**Determination of ED_{50} and C_{eff}**. The efficacious dose resulting in 50% antitumor efficacy (ED_{50}) was determined
using the MV522 model. MV522 tumor cells do not express functional VEGF or PDGF RTKs. In addition, the tumors have a moderate growth rate, making it an ideal model to evaluate the antiangiogenesis-associated ED50 of axitinib. Based on the relationship between dose and the corresponding TGI (Fig. 4A), the ED50 was determined to be 8.8 mg/kg twice daily (Supplementary Fig. S4) and a 30 mg/kg twice daily dose level corresponded to an ED70 in this model. The range of in vivo efficacious concentration (Ceff) corresponding to a 50% TGI was determined by evaluating the relationship between TGI (Fig. 4A) and plasma concentrations. Based on Cmin (trough concentration), the estimated unbound Ceff was determined to be 0.28 nmol/L (or 0.11 ng/mL; Fig. 4C, left); based on Cave (average concentration across 24 h), the calculated unbound Ceff was determined to be 0.85 nmol/L (0.33 ng/mL; Fig. 4C, right). Thus, the Ceff value range (0.28-0.85 nmol/L) is in agreement with the Ctarget value (0.5 nmol/L) obtained from in vivo target modulation studies.

The relationship between dose and target inhibition was further analyzed based on pharmacokinetic profiles, IC50 values, and tumor size at the end of dosing period. Table 2 summarizes the single-agent antitumor efficacy of axitinib in nonclinical models. The table includes the disease type, description, dose regimen, size at start of dosing, dosing period, TGI, and survival assessment.

### Table 2. Summary of single-agent antitumor efficacy of axitinib in nonclinical models

<table>
<thead>
<tr>
<th>Disease type</th>
<th>Description</th>
<th>Dose (mg/kg)</th>
<th>Regimen</th>
<th>Size at start of dosing (mm³)</th>
<th>Dosing period (d)</th>
<th>TGI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colon carcinoma</td>
<td>Dose-dependent TGI in MV522 model</td>
<td>1</td>
<td>orally twice daily</td>
<td>170</td>
<td>16</td>
<td>18.3</td>
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<td>3</td>
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<td>15.2</td>
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<td>10</td>
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<td>80.3</td>
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<td>150</td>
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<td>94.6</td>
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<td>200</td>
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<td>96.3</td>
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<td>Dose response TGI in HT29 model</td>
<td>10</td>
<td>orally twice daily</td>
<td>110</td>
<td>16</td>
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<td>150</td>
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<td>TGI in orthotopic HTC-116 GFP model</td>
<td>30</td>
<td>orally twice daily</td>
<td>1 d after implant</td>
<td>10</td>
<td>Unreliable</td>
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<td>80</td>
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<tr>
<td>Lung</td>
<td>Dose-dependent efficacy in LLC model</td>
<td>1</td>
<td>orally twice daily</td>
<td>&lt;50</td>
<td>18</td>
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<td>300</td>
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<td>TGI and antimetastasis activity and survival assessment in LLC model</td>
<td>100</td>
<td>orally twice daily</td>
<td>Prophylactic dose (s.c. model)</td>
<td>38</td>
<td>Survival ~ 11 d median survival vs control</td>
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<td></td>
<td></td>
<td>orally twice daily</td>
<td>Tail vein implanted tumors</td>
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<td></td>
<td>TGI in KIT+ NCI-H526 SCLC model</td>
<td>30</td>
<td>orally twice daily</td>
<td>180</td>
<td>13</td>
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<td>Melanoma</td>
<td>TGI in established A375 melanoma</td>
<td>10</td>
<td>orally twice daily</td>
<td>336</td>
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<td>Dose-dependent TGI in activating mutant b-Raf A2058 melanoma model</td>
<td>3</td>
<td>orally twice daily</td>
<td>150</td>
<td>15</td>
<td>36</td>
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<td>83</td>
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<tr>
<td>Renal carcinoma</td>
<td>TGI in orthotopically implanted SN12C GFP human renal carcinoma model</td>
<td>10</td>
<td>orally twice daily</td>
<td>2 d after implant</td>
<td>41</td>
<td>54</td>
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<td></td>
<td>Glioma</td>
<td>Dose-dependent efficacy in U87 glioma model</td>
<td>10</td>
<td>orally twice daily</td>
<td>46-72</td>
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<td>NHL</td>
<td>Efficacy in human lymphoma model</td>
<td>50</td>
<td>orally twice daily</td>
<td>1 d after implant</td>
<td>14</td>
<td>Significant reduction in i.p. tumor burden as indicated by reduction in body weights</td>
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<td></td>
<td>Namalwa (time course)</td>
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<td></td>
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**NOTE:** TGI (%) was calculated according to the equation: [1 - ΔTreat/ΔControl] × 100, where ΔTreat and ΔControl are changes of tumor volume between the end of the dosing and the beginning of the dosing for a treated group and a control group, respectively.
C_{target} and C_{eff}. Plasma concentrations at 10 mg/kg (ED_{50} dose) and 30 mg/kg (ED_{70} dose) were both above and near C_{target} (for VEGFRs) and C_{eff} (TGI-based) during the majority of the day (Fig. 4D). However, the plasma concentrations at these doses only allowed a total of ~5 and 12 h coverage over the cellular IC_{50} of PDGFR-β, respectively (anti-PDGFR-based C_{target} or C_{eff} from in vivo studies is not available). Based on this analysis, the antitumor efficacy at 10 mg/kg in the MV522 model (VEGFR-null, PDGFR-null) appeared to be mainly driven from vascular VEGFR inhibition by axitinib. In the same model, infusions of axitinib achieved a near maximal antitumor efficacy (80%) that was associated with a steady-state plasma concentration greater than the cellular IC_{50} for VEGFRs but below the cellular IC_{50} for PDGFR-β (data not shown).

Axitinib enhances antitumor efficacy of chemotherapeutic agents in multiple tumor models. The antitumor efficacy of axitinib was assessed in combination with docetaxel (in LLC and human breast cancer models), carboplatin (in a human

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**Fig. 4.** Antitumor efficacy and pharmacokinetic/pharmacodynamic correlation of axitinib. **A,** axitinib dose-dependent inhibition of tumor growth in MV522. Tumor cells (2 \times 10^6) were inoculated into the right upper flank of nu/nu mice. Tumors were randomized according to tumor size and axitinib treatment was initiated on day 7. Mean ± SE. ■, control; ▲, axitinib 0.3 mg/kg; ●, axitinib 1 mg/kg; ○, axitinib 3 mg/kg; ▼, axitinib 10 mg/kg; ◆, axitinib 30 mg/kg; ▼, axitinib 100 mg/kg; ◆, axitinib 150 mg/kg. **B,** axitinib inhibition of microvesSEL growth compared with the control as shown by CD31 staining (clone Mec13.3; PharMingen). Highly positive vessel staining (brown) is shown in the control group compared with the axitinib-treated group. Axitinib treatment also induced the level of caspase-3 and reduced Ki-67 staining in MV522 tumors. Antibody 9661L (Cell Signaling) and RM9106 (LabVision/NeoMarkers) were used as the primary antibodies for caspase-3 and Ki-67, respectively. All images were taken at \( \times 20 \) magnification. **C,** derivation of EC_{50} of axitinib from the MV522 TGI study. The %TGI ± SE was plotted against either C_{min} (left) or C_{ave} (right) plasma concentrations corresponding to the different dose levels to derive EC_{50}. Curve fit and calculation of EC_{50} values using the sigmoidal dose-response nonlinear regression model (Prism, GraphPad) are shown. To facilitate the curve fit, a close to 0% TGI was assigned to an artificial plasma concentration of 1/100 of the lowest measurable value. The curve fit was nonrestrictional at the high concentration end (a 100% TGI was not enforced for curve fit). **D,** axitinib preferentially inhibited VEGFRs at the ED_{50} and ED_{70} doses. The pharmacokinetic profile is created by plotting the plasma concentrations (± SE) against the time points of treatment at 10 mg/kg twice daily (▲) and 30 mg/kg twice daily (■). The pharmacokinetic profile was analyzed against the derived C_{target} (0.5 nmol/L) and C_{eff} (0.28-0.85 nmol/L) of axitinib. IC_{50} values for VEGFR-2 (0.2 nmol/L) and PDGFR-β (1.6 nmol/L) are also shown. The duration of action against VEGFRs and PDGFR-β is assessed based on this correlative analysis.
ovarian cancer model), or gemcitabine (in a human pancreatic cancer model). These models were chosen because they have only low or moderate sensitivity to chemotherapies in mice.

In the LLC model, axitinib (10 or 30 mg/kg orally twice daily) in combination with a maximally tolerated dose of docetaxel (40 mg/kg once a week) enhanced tumor growth delay, defined as the increase in the median time to the end point (TTE) in a treatment group compared with the control group. A TTE (a measure of disease progression) is defined as tumor size $= 1,500 \text{ mm}^3$ or animal moribund due to tumor burden or metastasis. A 54% or 100% tumor growth delay was obtained for docetaxel plus 10 or 30 mg/kg axitinib versus a 9%, 30%, and 60% for docetaxel alone and 30 and 60 mg/kg axitinib alone, respectively (data not shown). Docetaxel plus axitinib significantly delayed disease progression compared with docetaxel alone (Fig. 5A).

In the MDA-MB-435/HAL-luc xenograft model (Fig. 5B), dose scheduling study of axitinib and gemcitabine in human pancreatic carcinoma model BxPC-3. Xenografts were initiated by s.c. implanting a $1\text{ mm}^3$ BxPC-3 tumor fragment in the right flank of each mouse. Treatments began when tumors were $90 \text{ mm}^3$ in size. Axitinib was dosed at 30 mg/kg orally twice daily for 60 d (60d) except for the last two groups; gemcitabine (Gem) was given at 140 mg/kg i.p. 3 times per day for 4 d for either one cycle (1C) or three cycles (3C). Tumors were measured twice weekly and animals were euthanized when their tumors reached an endpoint volume of $1,200 \text{ mm}^3$ or on 60 d of treatment, whichever came first. Data shown are tumor sizes at 53 d of treatment. The control and gemcitabine single groups are not included because all tumors in these groups reached the $1,200 \text{ mm}^3$ end point before day 53. Statistical significance was determined by ANOVA with a Tukey’s multiple comparison test.

C, combination therapy of axitinib and bevacizumab significantly inhibited spontaneous lymph node metastasis and prolonged survival of animals in the M24met model. Primary tumors were surgically removed once they reached the size of 200 to 300 mm$^3$, which enhanced tumor metastasis to lymph nodes and the lung. Lymph node tumors were measured until the predetermined survival end point (total lymph node tumor size $= 2,000 \text{ mm}^3$). Treatment with axitinib (80 mg/kg orally twice daily), bevacizumab (5 mg/kg i.v. 2xqw), or the combination of the two agents began 1 d post-surgery and continued until the end of the study. Lymph node tumor volume comparison after 33-day treatments is shown. Mean $\pm$ SE. D, a Kaplan-Meier plot showed significant delay of disease progression with combination therapy compared with either single-agent alone. Combination group ($\bullet$) $P < 0.0001$, versus axitinib (60 mg/kg; $\bigtriangleup$) and $P = 0.0076$, versus bevacizumab (5 mg/kg; $\bigtriangledown$). n, control.
model, axitinib (30 mg/kg) and docetaxel (5 mg/kg; 25% of murine maximally tolerated dose) produced a robust tumor growth delay as shown by the reduction of tumor bioluminescent signal (Supplementary Fig. S5) and increase in the number of complete responders compared with either single agent alone (data not shown).

The antitumor efficacy of axitinib in combination with gemcitabine was investigated against various dosing schedules in the gemcitabine-resistant BxPC-3 human pancreatic cancer model (Fig. 5B). In one study, single-agent gemcitabine (140 mg/kg i.p., days 1, 4, 7, and 10, either one-cycle or three-cycle treatments) or axitinib (30 mg/kg orally twice daily) delayed tumor growth. In the groups receiving gemcitabine plus axitinib, the “early dosing” of axitinib (day 1, group 5) produced a greater tumor growth delay than “late dosing” (starting axitinib on day 11 (group 6) or 16 (group 7) after initiation of gemcitabine) regardless of the number of gemcitabine cycles; with the same axitinib regimen, three gemcitabine treatment cycles (group 8, 9, 10) produced a greater efficacy than one gemcitabine treatment cycle (group 5, 6, 7). Alternating dose of the two agents (group 12) or early termination of axitinib (group 11) resulted in a significant compromise in tumor growth delay compared with coadministration and continuous twice daily dosing of axitinib.

**Combination of axitinib and bevacizumab produced significant antitumor activity in M24met model.** The ability of axitinib to enhance bevacizumab efficacy in the orthotopically implanted and spontaneous metastasis human melanoma M24met tumor model was investigated; M24met tumors do not express functional RTKs (data not shown). Most importantly, circulating human VEGF-A, the ligand for bevacizumab, was found to be >95% of total circulating VEGF-A in *in vivo* in this model.

In this study, both axitinib (60 mg/kg orally twice daily) and bevacizumab (5 mg/kg i.v., 2xqw) exhibited moderate single-agent activity against lymph node tumor metastasis. The combination of the two agents significantly improved antitumor efficacy assessed based on reduction of lymph node tumor mass (Fig. 5C), angiogenesis (Supplementary Fig. S6), and proliferation index of metastatic lymph node tumors (Supplementary Fig. S7). In addition, the combination therapy significantly prolonged animal survival measured by reduction of time to progression (TTE), with a 13-day TTE for both single agents versus the control and a 20-day TTE for combination therapy versus the control (Fig. 5D). As expected, dosing with bevacizumab or bevacizumab plus axitinib, but not axitinib single-agent treatment, significantly reduced free plasma human VEGF-A (data not shown).

**Discussion**

Axitinib was generated from an iterative structure-based drug design approach and is a potent (picomolar) and selective inhibitor of VEGF RTKs 1, 2, 3. The compound exhibits ~8-fold lower inhibitory activity against PDGFRs and KIT and has little activity against other type III and V family kinases (CSF-1R, Flt-3, FGFR-1, and RET), epidermal growth factor receptor, and c-Met. Axitinib is highly selective against nonreceptor kinases and proteins in a variety of off-target screening assays.

Axitinib dose-dependently inhibits endothelial cell proliferation, survival, and three-dimensional tube formation *in vitro*. Axitinib rapidly blocks downstream signal transduction via the eNOS/Akt pathway that has been implicated in the pathologic angiogenesis and normal vascular homeostasis (33, 34). The required concentrations for eNOS and Akt phosphorylation inhibition track with that for VEGFR-2 phosphorylation inhibition by axitinib. Furthermore, phospho-eNOS inhibition was reversible with the signal fully recovered soon after (1-2 h) withdrawal of axitinib (whereas inhibition of phospho-VEGFR-2 was sustained for up to 8 h; data not shown). Consistent with these findings is the observation that, in the clinic, axitinib-associated increases in diastolic blood pressure are reversible and closely correlate with clinical outcome (35).

*In vivo*, axitinib markedly inhibited vascular VEGFR-2 phosphorylation in (a) the development rat ocular angiogenesis model, (b) the VEGF-mediated skin permeability model of mice, and (c) the vasculature of a human xenograft tumor model in mice. In addition, the *C*~target~ values derived from the rat ocular angiogenesis model and the mouse permeability model (~0.5 nmol/L) are consistent with the efficacy-based *C*~eff~ value (0.28-0.85 nmol/L) obtained from TGI studies. Furthermore, the *C*~eff~ value derived from these nonclinical studies in general agrees with the range of plasma concentrations of the 5 mg twice daily clinical starting dose of axitinib (*C*~max~ = 0.19 ± 0.12 nmol/L; interim data). This clinical dose is associated with reduced tumor permeability and blood flow (19), tumor shrinkage (RECIST), overall response rate, and survival benefit observed in multiple phase II axitinib single-agent and combination studies in the clinic (22–25).

Axitinib alone produced marked antitumor efficacy that was associated with antiangiogenesis effects across nonclinical models regardless of the RTK expression profile in the tumor cells. This may imply that axitinib may have broad indications and utility in the clinic. In addition, based on published information and this report, we believe that vascular VEGFR inhibition alone by axitinib is essential and sufficient to produce significant antiangiogenesis and meaningful antitumor activity. In animal models, this activity can be achieved with a 10 to 15 mg/kg orally twice daily administration of axitinib. Higher dose levels of axitinib (>30 mg/kg) in mice have been shown to produce a *C*~max~ exposure significantly above the *IC*~50~ for PDGFR and typically were associated with greater antitumor efficacy (see Fig. 4A); we believe that although a transient PDGFR inhibition may have partially contributed to the efficacy, a more sustained and prolonged inhibition of VEGFR-2 throughout the majority of the day played a significant role in efficacy enhancement. The latter is consistent with the preliminary nonclinical data that equal or even greater efficacy can be achieved through continuous infusion of axitinib with a steady-state plasma concentration lower than PDGFR *IC*~50~. Furthermore, in the RIP-Tag2 transgenic tumor model in which axitinib at efficacious dose levels (up to 25 mg/kg) produced rapid and dramatic inhibition of tumor endothelial cell fenestration, VEGFR-2 expression, vessel growth, and vascular density but did not decrease PDGFR expression or tumor vasculature-associated pericytes, there was, however, evidence that certain markers on the pericytes were modulated (36, 37). The interpretation of the latter remains to be addressed. Based on our nonclinical and clinical pharmacokinetic/pharmacodynamic understanding, *C*~max~ of the current clinical starting dose of axitinib (5 mg twice daily) in general does not exceed the *IC*~50~ for PDGFR in the majority
Motzer RJ, Hutson TE, Tomczak P, et al. Sunitinib to promote processes leading to sustained tumor progression. These growth factors interact with each other synergistically. VEGFR-3, VEGFR-1, VEGFR-2, and neuropilin (48). Furthermore, these growth factors interact with each other synergistically to promote processes leading to sustained tumor progression (45, 46). In this context, small-molecule VEGF RTKIs may have advantage over VEGF-A-selective bevacizumab. Finally, a recent report showed that intracellular autonomous VEGF/VEGFR-2 signaling had an indispensable role in vascular homeostasis and endothelial cell survival (49) and that intracellular VEGFR-2 activation in wild-type cells was suppressed by a small-molecule VEGFR antagonist but not by bevacizumab. The implication of intracellular VEGFR-2 inhibition in the context of tumor angiogenesis remains to be elucidated; however, it is conceivable that membrane permeable axitinib, but not bevacizumab, may potently inhibit intracellular VEGFR-2 signaling (in addition to inhibiting VEGF autophosphorylation mediated by exogenous VEGF) in tumor endothelial cells that ultimately induce endothelial cell apoptosis that cannot be rescued by exogenous VEGF. Although clinically combining axitinib and bevacizumab may not be feasible due to overlapping mechanism-based adverse events such as hypertension, we believe that, in principle, combining intracellular and extracellular inhibition of VEGF signaling would lead to robust and prolonged antiangiogenesis.

In summary, axitinib is a potent and selective inhibitor of VEGFR-1, VEGFR-2, and VEGFR-3 with proven antitumor activity from nonclinical and clinical studies. Axitinib may evolve to become one of the most promising oral VEGF RTKIs with significant single-agent antitumor activity and combinability for the treatment of a broad spectrum of human malignancies.

Disclosure of Potential Conflicts of Interest

No potential conflict of interest were disclosed.

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References


Clinical Cancer Research

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