Targeting the PI3K Pathway in the Brain—Efficacy of a PI3K Inhibitor Optimized to Cross the Blood–Brain Barrier


Abstract

Purpose: Glioblastoma (GBM), the most common primary brain tumor in adults, presents a high frequency of alteration in the PI3K pathway. Our objectives were to identify a dual PI3K/mTOR inhibitor optimized to cross the blood–brain barrier (BBB) and characterize its brain penetration, pathway modulation in the brain and efficacy in orthotopic xenograft models of GBM.

Experimental Design: Physicochemical properties of PI3K inhibitors were optimized using in silico tools, leading to the identification of GNE-317. This compound was tested in cells overexpressing P-glycoprotein (P-gp) or breast cancer resistance protein (BCRP). Following administration to mice, GNE-317 plasma and brain concentrations were determined, and phosphorylated biomarkers (pAkt, p4EBP1, and pS6) were measured to assess PI3K pathway suppression in the brain. GNE-317 efficacy was evaluated in the U87, GS2, and GBM10 orthotopic models of GBM.

Results: GNE-317 was identified as having physicochemical properties predictive of low efflux by P-gp and BCRP. Studies in transfected MDCK cells showed that GNE-317 was not a substrate of either transporter. GNE-317 markedly inhibited the PI3K pathway in mouse brain, causing 40% to 90% suppression of the pAkt and pS6 signals up to 6-hour postdose. GNE-317 was efficacious in the U87, GS2, and GBM10 orthotopic models, achieving tumor growth inhibition of 90% and 50%, and survival benefit, respectively.

Conclusions: These results indicated that specific optimization of PI3K inhibitors to cross the BBB led to potent suppression of the PI3K pathway in healthy brain. The efficacy of GNE-317 in 3 intracranial models of GBM suggested that this compound could be effective in the treatment of GBM.

Introduction

The phosphatidylinositol 3-kinase (PI3K) pathway plays a key role in cell survival, growth and proliferation (1). The lipid kinases belonging to the PI3K family phosphorylate the 3'-hydroxyl group of phosphatidylinositols, which lead to the activation of the serine/threonine protein kinase Akt. Further downstream effectors include the mTOR complex 1 and S6 kinase. From the 3 classes of PI3K, class Ia is the most widely involved in cancer and its kinases are composed of a catalytic (p110α, p110β, or p110δ) and a regulatory subunit (p85 or p55). The phosphatase PTEN acts as a tumor suppressor and inhibits PI3K pathway signaling (2).

PI3K deregulation, through activating mutations of the p110α catalytic subunit or suppression of PTEN, has been associated with the development of numerous cancers (3). More specifically, alteration of this pathway has been detected in more than 80% of glioblastoma (GBM; refs. 4, 5). GBM is the most common and aggressive primary tumor of the central nervous system (CNS) in adults. This high grade glioma, characterized by rapid growth and diffuse invasiveness (6), presents very few treatment options. Tumor progression is controlled only for a limited time with a median survival duration of less than 2 years after initial diagnosis (7). Key signaling proteins of the PI3K pathway are mutated in a large proportion of GBM, leading to persistent activation of the pathway; EGFR amplification and/or mutation, mutation of the PI3K catalytic and regulatory subunits, and loss of PTEN protein are detected in 45%, 10%, and 50% of GBM, respectively (4). Thus, targeting the PI3K pathway represents an attractive therapeutic approach for brain tumors. Inhibitors of mTOR, a key mediator of PI3K signaling, have been evaluated in Phase...
I and II clinical trials as single agents or in combination with receptor tyrosine kinase inhibitors with limited success (4). These compounds, analogues of rapamycin, mostly target mTORC1. This in turn can trigger a feedback loop, possibly through mTORC2, which results in the activation of Akt (6, 8). Recent work from Tanaka and colleagues also points to a role of mTORC2 signaling, independent of mTORC1, in GBM (9). The disappointing results with rapalogues may also be attributed to the failure of the drugs to fully access their target (4). These 2 points underscore the potential improvement in activity that could be achieved with dual PI3K/mTOR inhibitors (mTORC1 and mTORC2) as well as the challenge in crossing the BBB and overcoming the protective effect of efflux transporters to reach the brain and tumors with anticancer agents.

The objectives of the studies presented here were to identify a potent dual PI3K/mTOR inhibitor possessing physicochemical properties specifically optimized for brain penetration, and test whether this compound, GNE-317 (Fig. 1A), could show PI3K pathway suppression in the brain and superior efficacy in intracranial models of GBM.

**Materials and Methods**

**Chemicals**

All GNE compounds, including GNE-317, GDC-0941, and GDC-0980, were synthesized by Genentech, Inc. All solvents used in analytic assays were purchased from Thermo Fisher Scientific and were of analytic or high-performance liquid chromatography grade. All other chemicals and reagents were purchased from Sigma-Aldrich unless specified.

**Determination of physicochemical properties and Central Nervous System Multiparameter Optimization (CNS-MPO) score**

Using MoKa Software (version 1.1.0, Molecular Discovery) and a custom pKa model augmented with Roche internal data, logarithm of the acid dissociation constant of most basic center (cpK_a_MB), logarithm of the partition coefficient (log P), and CNS-MPO score were calculated.

**Translational Relevance**

Activation of the PI3K pathway, through mutations of its components, is observed in more than 80% of glioblastoma (GBM), the most common and aggressive type of malignant primary brain tumor. This pathway can also be activated by therapeutic interventions, such as radiation and chemotherapy. Thus, inhibition of the PI3K pathway represents an attractive therapeutic approach for GBM. However, the diffusely infiltrative nature of GBM requires the pharmacologic agents to cross the blood–brain barrier (BBB). Here we show that GNE-317, a PI3K/mTOR inhibitor that was specifically designed to cross the BBB, achieved potent suppression of the PI3K pathway in the brain of mice with intact BBB. GNE-317 was also efficacious in 3 orthotopic models of GBM, U87, GS2, and GBM10. These results suggest that PI3K suppression and GBM tumor growth inhibition may be achieved in patients, including in areas with intact BBB, provided that efficient brain and tumor penetration is obtained.
coefficient (clogP), and logarithm of the distribution coefficient at pH 7.4 (clogD) were calculated. Using OEChem tools (OpenEye Scientific Software), molecular mass (MM), topologic polar surface area (TPSA), number of hydrogen bond donors (HBD) were computed for molecules in their neutral form. CNS-MPO scores were calculated using the formula proposed by Wager and colleagues (10). To verify our implementation of CNS-MPO, we compared our scores with the published data set and found an excellent correlation.

**In vitro transport assays**

Madin-Darby canine kidney (MDCK) cells heterologously expressing human P-gp, human BCRP or mouse Bcrp1 and LLC-PK1 cells transfected with mouse P-gp (mdr1a) were used to determine whether GNE-317 was a substrate of these transporters. MDRI-MDCKI cells were licensed from the National Cancer Institute whereas Bcrp1-MDCKII, BCRP-MDCKII, and Mdr1a-LLC-PK1 cells were obtained from the Netherlands Cancer Institute. For transport studies, cells were seeded on 24-well Millicell plates (Millipore) 4 days before use (polyethylene terephthalate membrane, 1 μmol/L pore size) at a seeding density of 2.5 × 10^5 cells/mL (except for MDRI-MDCKI, 1.3 × 10^5 cells/mL). GNE-317 was tested at 5 μmol/L in the apical to basolateral (A-B) and basolateral to apical (B-A) directions. The compound was dissolved in transport buffer consisting of Hank’s balanced salt solution (HBSS) with 10 mmol/L HEPES (Invitrogen Corporation). Lucifer Yellow (Sigma-Aldrich) was used as the paracellular marker. GNE-317 concentrations in the donor and receiving compartments were determined by liquid chromatography/tandem mass spectrometry (LC-MS/MS) analysis. The apparent permeability (P_{app}), in the A-B and B-A directions, was calculated after a 2-hour incubation as: \( P_{app} = \frac{dQ/dt}{C_{AC0}} \), where \( dQ/dt \) is the rate of compound appearance in the receiver compartment; \( A \) is the surface area of the insert; and \( C_0 \) is the initial substrate concentration at \( T_0 \).

The efflux ratio (ER) was calculated as \( \frac{P_{app, B-A}}{P_{app, A-B}} \).

**Determination of plasma protein and brain binding**

The extent of protein binding of GNE-317 was determined in vitro, in mouse plasma (Bioreclamation, Inc.) by equilibrium dialysis using a HTDialysis 96-well block (HTDialysis LLC). GNE-317 was added to pooled plasma (n ≥ 3) at a total concentration of 10 μmol/L. Plasma samples were equilibrated with phosphate-buffered saline (pH 7.4) at 37°C in 90% humidity and 5% CO2 for 4 hours. Following dialysis, concentration of GNE-317 in plasma and buffer was measured by LC-MS/MS. The percentage GNE-317 unbound in plasma was determined by dividing the concentration measured in the postdialysis buffer by that measured in the postdialysis plasma and multiplying by 100. Incubations were carried out in triplicate. Parameters are presented as mean ± standard deviation (SD).

The free fraction of GNE-317 in mouse brain was determined as described by Kalvass and colleagues (11). In brief, brain tissue was homogenized in 3 volumes of phosphate-buffered saline and GNE-317 was added at a final concentration of 10 μmol/L. Aliquots of 300 μL were dialyzed in a RED device (Thermo Scientific) against a volume of 500 μL buffer for 4 hours at 37°C in an incubator at 90% humidity and 5% CO2. Following dialysis, tissues, and buffer samples were analyzed as described for the plasma protein binding studies.

**In vivo studies**

All studies conducted were approved by the Institutional Animal Care and Use Committee at Genentech, Inc. or the Mayo Institutional Animal Care and Use Committee.

**Pharmacokinetic study in mouse**

Twelve female CD-1 mice (Charles River Laboratories) were given a 50 mg/kg oral (PO) dose of GNE-317 in 0.5% methylcellulose/0.2% Tween 80 (MCT). Two blood samples of approximately 0.15 mL were collected from each mouse (n = 3 mice per timepoint) by retro-orbital bleed or terminal cardiac puncture whereas the animals were anesthetized with isoflurane. Blood samples were collected in tubes containing K2EDTA as the anticoagulant, predose and at 0.083, 0.25, 0.5, 1, 3, 6, 9, and 24 hours postdose. Samples were centrifuged within 1 hour of collection and plasma was collected and stored at −80°C until analysis. Total concentrations of GNE-317 were determined by LC-MS/MS, following plasma protein precipitation with acetonitrile, and injection of the supernatant onto the column, a Varian MetaSil AQ C18 column (50 mm × 2 mm, 5 μm particle size). A CIC HTS PAL autosampler (LEAP Technologies) linked to a Shimadzu SCL-10A controller with LC-10AD pumps (Shimadzu), coupled with an AB Sciex API 4000 triple quadrupole mass spectrometer (AB Sciex) were used for the LC-MS/MS assay. The aqueous mobile phase was water with 0.1% formic acid and the organic mobile phase was acetonitrile with 0.1% formic acid. The lower and upper limits of quantitation of the assay were 0.005 and 10 μmol/L, respectively. The total run time was 1.5 minutes and the ionization was conducted in the positive ion mode. Brains were collected at 1 and 6 hours postdose from 3 different animals at each time point, rinsed with ice-cold saline, weighed and stored at −80°C until analysis. Following dialysis, concentration of GNE-317 in plasma and buffer was measured by LC-MS/MS. The percentage GNE-317 unbound in plasma was determined by dividing the concentration measured in the postdialysis buffer by that measured in the postdialysis plasma and multiplying by 100. Incubations were carried out in triplicate. Parameters are presented as mean ± standard deviation (SD).

The free fraction of GNE-317 in mouse brain was determined as described by Kalvass and colleagues (11). In brief, brain tissue was homogenized in 3 volumes of phosphate-buffered saline and GNE-317 was added at a final concentration of 10 μmol/L. Aliquots of 300 μL were dialyzed in a RED device (Thermo Scientific) against a volume of 500 μL buffer for 4 hours at 37°C in an incubator at 90% humidity and 5% CO2. Following dialysis, tissues, and buffer samples were analyzed as described for the plasma protein binding studies.

**Modulation of pAKT, p4EBP1, and pS6 in brain**

Female CD-1 mice were administered a single PO dose of GNE-317 at 50 mg/kg. Brains and plasma were collected at 1 and 6 hour postdose, from 3 animals at each time point. Individual brains were split in half for PD analysis and GNE-317 concentration measurement. The samples were stored at −70°C and analyzed for GNE-317 total concentration as described previously. For PD analysis, cell
Efficacy studies in brain tumor models

Three human glioma models were used in the in vivo studies: The U-87 MG/M (U87) glioblastoma cancer cells (a Genentech variant of U-87 MG cells from American Type Culture Collection), the GS 2.Luc cells (GS2) derived from studies: The U-87 MG/M (U87) glioblastoma cancer cells (a xenografts were administered GNE-317 (40 mg/kg), GDC-0941 (250 mg/kg), GDC-0980 (10 mg/kg), or vehicle (MCT) PO daily for 6 weeks starting 14 days posttumor cell inoculation. Mouse body weights were recorded twice per week during the study and animals were euthanized if body weight loss was greater than 20% from their initial body weight. Mice bearing intracranial xenografts from GBM10 were treated with the vehicle alone or GNE-317. GNE-317 was administered PO daily, initially at a dose of 40 mg/kg/day for 2 weeks and then subsequently at 30 mg/kg/day. All GBM10 tumor-bearing mice were observed daily and euthanized upon reaching a moribund state. Tumor volumes were monitored by ex vivo micro-CT and T2 MRI for the GBM models U87 and GS2, respectively. The differences between treatment groups were evaluated using the Dunnett’s t test in JMP (SAS Institute). MRI was carried out on a Varian 9.4T MRI system with a 30 mm quadrature volume coil. During the imaging, animals were kept under anesthesia with 2% isoflurane in air. Body temperature was continuously monitored using a rectal probe and was maintained at 37°C by a heated-air flow system regulated by in-house LabVIEW controller software. A T2-weighted fast spin echo, multi-slice (FSEMS) sequence was used to detect lesions by MRI. Twelve to twenty axial 0.5 to 0.8-mm-thick slices were acquired with a 20 mm × 20 mm field of view (FOV), and 128 × 128 matrix, zero-filled to 256 × 256 images. TR = 3,500 to 4,000 ms, TE = 9 to 10 ms, ET1 = 8, k-zero = 4, NEX = 8. The BBB integrity was evaluated by dynamic contrast enhanced MRI (DCE-MRI). Precontrast 3D gradient echo (3DGE) datasets were acquired at 2° and 10° flip angles, TR = 8.3 ms, TE = 1.1 ms, NEX = 4, FOV = 20 × 20 × 8 mm, matrix = 64 × 64 × 16. A 50 μl bolus injection of Gd-based Gadodiamide (Omniscan) contrast agent was injected via a tail vein catheter following collection of the precontrast images. Postcontrast 3DGE images were then acquired approximately every 10 seconds for 30 minutes (10° flip angle, NEX = 1). Tumor volumes were calculated from the T2-weighted FSEMS images using an intensity threshold based region growing tool in MRVision software. Sample preparation, scanning, and image analysis for ex-vivo micro-computed tomography (micro-CT) imaging were carried out as described previously (15). In the studies conducted with the GS2 tumor-bearing mice, plasma and brains were also collected at the end of treatment to measure the concentration of each compound. Each brain was bisected into a normal and tumor-bearing hemisphere. Plasma and brains were processed and analyzed by LC-MS/MS as described previously.

Modulation of the PI3K pathway in intracranial tumors

The effects of GNE-317 and GDC-0941 on the PI3K pathway in GS2 and U87 orthotopic tumors were evaluated by immunohistochemistry (IHC) following a single PO dose of GDC-0941 (250 mg/kg) or GNE-317 (40 mg/kg) to mice. Brains were collected 1 hour postdose, after the animals had been anesthetized with pentobarbital, perfused first with heparinized phosphate-buffered saline and subsequently with 4% paraformaldehyde.
IHC for detection of pAKT with antibody D9E (Cell Signaling Technologies) was carried out on 4-μ-thick paraffin-embedded tissue sections using a Discovery XT autostainer and CC1 standard antigen retrieval (Ventana Medical Systems). Specifically bound primary antibody was detected using Omnimap detection (Ventana) and hematoxylin counterstain.

Results

Optimization of physicochemical properties

Calculated physicochemical parameters (cLogP, cLogD, cpKa, MM, TPSA, and HBD) were used to determine the Central Nervous System Multiparameter Optimization (CNS-MPO) score. Higher ERs in MDCK cells transfected with P-gp (Supplementary Fig. 1A) or bcrp1 (Supplementary Fig. 1B) were associated with lower values of the CNS-MPO score. In addition, most compounds with ER lower than 3 (cut-off value for our assay) also appeared to present CNS-MPO scores greater than 4.5; 16 of 21 compounds in the P-gp assay, and 22 of 23 compounds in the bcrp1 assay. In contrast, the majority of the compounds with ER greater than 3 had a CNS-MPO score lower than 4.5 in both assays.

Transport studies in transfected cell lines

The bidirectional transport of GNE-317 was assessed in transfected cell lines overexpressing human or mouse P-gp or BCRP. The apparent permeability (P_{app}) was high and comparable to that determined for metoprolol, the high expression of the human or mouse P-gp and BCRP, and 22 of 23 compounds in the bcrp1 assay. The brain-to-plasma ratio of total concentrations remained unchanged and was approximately 1 between 1 and 6 hours postdose (Table 2). Free brain-to-free plasma concentrations ratio was 0.3.

Modulation of pAkt, p4EBP1, and pS6 in brain

The levels of pAkt, p4EBP1, and pS6 (downstream markers of the PI3K/mTOR pathway) measured in the brain of normal mice that received a single oral dose of GNE-317 (50 mg/kg) were significantly lower than those in the control normal mice that received a single oral dose of GNE-317 (50 mg/kg) were significantly lower than those in the control animals (Fig. 1C), with suppression of pAkt, p4EBP1, and pS6 reaching 80%, 84%, and 92%, respectively, 1 hour postdose and remaining greater than 55% 6 hours postdose for pAkt and pS6 (Fig. 1D). Levels of p4EBP1 were back to baseline 6 hours postdose.

Efficacy in brain tumor models

The efficacy of GNE-317 was tested in 3 intracranial tumor models, the U87, the neurosphere GS2 and the GBM10 models. GNE-317 was administered PO at 40 mg/kg daily for 3 and 6 weeks to U87 and GS2 tumor-bearing mice, respectively, and for more than 12 weeks to GBM10 tumor-bearing mice. The effect of the treatment on the U87 and GS2 tumor volumes was assessed at the end of the dosing period. A U87 tumor image obtained by micro-CT is presented in Fig. 1B. Plasma concentrations remained fairly constant and higher than 2 μmol/L up to 9 hours postdose. GNE-317 free brain concentrations between 1 and 6 hours were higher than 0.1 μmol/L, suggesting that GNE-317 would be able to modulate the PI3K pathway in the brain. The brain-to-plasma ratio of total concentrations remained unchanged and was approximately 1 between 1 and 6 hours postdose (Table 2). Free brain-to-free plasma concentrations ratio was 0.3.

Pharmacokinetics of GNE-317 in mouse

The plasma concentrations-time profile of GNE-317 following a single PO administration (50 mg/kg) to mice is presented in Fig. 1B. Plasma concentrations remained fairly constant and higher than 2 μmol/L up to 9 hours postdose. GNE-317 free brain concentrations between 1 and 6 hours were higher than 0.1 μmol/L, suggesting that GNE-317 would be able to modulate the PI3K pathway in the brain. The brain-to-plasma ratio of total concentrations remained unchanged and was approximately 1 between 1 and 6 hours postdose (Table 2). Free brain-to-free plasma concentrations ratio was 0.3.

Plasma protein and brain tissues binding

Binding of GNE-317 to plasma proteins was moderate, with a free fraction (%) of 14.9 ± 1.6 (n = 3) in mouse plasma, when tested at 10 μmol/L. Binding to brain tissues was higher, with a free fraction of 5.4% ( ± 0.5; n = 3).

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Table 1. Apparent permeability (P_{app}) of GNE-317 in transfected cells

<table>
<thead>
<tr>
<th>Cell line</th>
<th>P_{app} (10^{-6} cm/s)</th>
<th>P_{app} ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A to B</td>
<td>B to A</td>
</tr>
<tr>
<td>MDR1-MDCKI</td>
<td>9.84 ± 0.66</td>
<td>15.1 ± 1.62</td>
</tr>
<tr>
<td>Bcrp1-MDCKII</td>
<td>16.2 ± 1.91</td>
<td>15.1 ± 2.48</td>
</tr>
<tr>
<td>BCRP-MDCKII</td>
<td>14.2 ± 1.13</td>
<td>16.0 ± 1.60</td>
</tr>
<tr>
<td>Mdr1a-LLC-PK</td>
<td>13.1 ± 0.61</td>
<td>15.7 ± 0.50</td>
</tr>
</tbody>
</table>

Results reported as mean ± S.D. (n = 3).

Table 2. Plasma concentrations, brain concentrations and brain-to-plasma ratio of GNE-317 following PO administration (50 mg/kg) to mice

<table>
<thead>
<tr>
<th>Time postdose (hours)</th>
<th>Total Brain (μmol/L)</th>
<th>Total Plasma (μmol/L)</th>
<th>Brain-to-plasma ratio</th>
<th>Free Brain (μmol/L)</th>
<th>Free Plasma (μmol/L)</th>
<th>Free Brain-to-plasma ratio</th>
</tr>
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<tbody>
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<td></td>
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<td></td>
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<tr>
<td>1</td>
<td>3.64 ± 0.95</td>
<td>3.63 ± 0.98</td>
<td>1.01 ± 0.05</td>
<td>0.19 ± 0.05</td>
<td>0.58 ± 0.15</td>
<td>0.33 ± 0.01</td>
</tr>
<tr>
<td>6</td>
<td>2.31 ± 1.82</td>
<td>2.10 ± 1.23</td>
<td>1.00 ± 0.27</td>
<td>0.12 ± 0.09</td>
<td>0.34 ± 0.19</td>
<td>0.33 ± 0.09</td>
</tr>
</tbody>
</table>

Results reported as mean ± S.D. (n = 3).
Bioluminescence measured before and at the end of treatment (Supplementary Table 1) displayed halted tumor growth with GNE-317, which was consistent with in vitro findings that showed cytostasis (Supplementary Fig. 2) but no cell death. Similarly, the GS2 tumors measured by MRI (Fig. 2A) in the treated mice were more than 50% smaller than those in the control group (Fig. 2B). GDC-0941, a PI3K inhibitor that does not cross the BBB (16), was also tested in these 2 models. In contrast to GNE-317, GDC-0941 showed no activity in the GS2 model (Fig. 2A and B), whereas it was able to reduce the U87 tumor volumes by 66% (Fig. 2C and D). To assess whether the absence of efficacy of GDC-0941 was related to its lack of mTOR inhibition, the dual PI3K/mTOR inhibitor GDC-0980 (17, 18) was also tested in the GS2 model. GDC-0980 is a substrate of P-gp and bcrp1 (19). Similarly to GDC-0941, GDC-0980 showed no activity against the GS2 model (Fig. 2A and B). Plasma and brain concentrations and brain-to-plasma ratios determined at the end of the study in the GS2 tumor-bearing mice are presented in Supplementary Table 2. For the 3 compounds, the brain concentrations and brain-to-plasma ratios were comparable in the normal part of the brain and in the tumored brain. In the GBM10 model, GNE-317 was able to extend the survival of mice from a median of 55.5 to 75 days (P < 0.05, log rank test; Fig. 2E) when administered at 30 mg/kg (40 mg/kg the first 2 weeks).

Inhibition of the PI3K pathway in intracranial tumors

Modulation of the PI3K pathway in the GS2 and U87 tumors was determined by IHC following a single PO dose of GNE-317 (40 mg/kg) or GDC-0941 (250 mg/kg). Tissue was probed with antibodies against pAkt. GNE-317 caused a marked reduction in staining for pAkt in the GS2 tumor (Fig. 3C) when compared with the untreated animal (Fig. 3A), and led to complete suppression of signal in the U87 tumor (Fig. 3F). In contrast, GDC-0941 treatment did not cause a noticeable change of pAkt staining in GS2 tumor when compared with control (Fig. 3A and B, respectively) whereas it led to a reduction in
intensity and density of pAkt staining in the U87 tumor (Fig. 3D and E).

**Permeability of the tumor vasculature**

The integrity of the BBB in the U87 and GS2 models was assessed by DCE-MRI. The T2-weighted images show the GS2 (Fig. 4A) and U87 (Fig. 4D) intracranial tumors. In the GS2 tumors, no contrast enhancement was detected following gadolinium injection in the T1-weighted images (Fig. 4B, precontrast; and Fig. 4C, postcontrast), indicating that the BBB was intact in this tumor model. Contrary to the GS2 model, marked contrast enhancement was observed in the U87 tumors (Fig. 4E and F), confirming the presence of an impaired BBB.

**Discussion**

The PI3K-Akt pathway is one of the most frequently altered signaling pathways in tumors (20). In addition, activating mutations of the p110α subunit, loss of the phosphatase PTEN or activation/amplification of upstream receptor tyrosine kinases are observed in more than 80% of GBM (5), the most common malignant primary brain tumor in adults. Increased pathway signaling is also
detected in response to current GBM treatments, such as radiation and chemotherapy (21, 22). Inhibiting this pathway in the brain remains challenging however, as compounds have to cross the BBB to reach their target. Although the BBB may be disrupted in most brain tumors (23), which allows some exposure to the compounds, spreading edges of neoplasms are frequently shielded by an intact BBB and the protective function of efflux transporters expressed in the endothelial cells of the brain capillaries (24). Thus, effective treatment of primary brain tumors or brain metastases can only be achieved with molecules that are able to cross the BBB. GNE-317 (Fig. 1A) was designed to bypass the 2 main transporters constituting the BBB, P-gp and BCRP.

To that end, we found that for the thienopyrimidine series of PI3K/mTOR inhibitors, the CNS-MPO score, an algorithm which assigns a numerical value to a balance of 6 distinct physicochemical properties (10), correlated with the likelihood of P-gp or bcrp1-mediated efflux. In an evaluation of more than 20 thienopyrimidines, a CNS-MPO score of less than 4.5 increased the probability that the compound would be substrate of both P-gp and bcrp1 (Supplementary Fig. 1). Therefore, newly designed compounds were evaluated in vitro before synthesis to ensure that the CNS-MPO score was greater than 4.5 (for additional discussion, see Heffron and colleagues, manuscript in preparation). Of the compounds designed according to the CNS-MPO guidelines, GNE-317, a selective (Supplementary Table 3) inhibitor of PI3K (p110α, K, 5 nM) and mTOR (K, 11 nM), with EC50 for growth inhibition of glioma cell lines ranging from 0.16 to 1.17 μmol/L (Supplementary Table 4), was further evaluated. This compound showed inhibition greater than 50% for 6 of the 59 kinases included in the panel when tested at 1 μmol/L (all free compound). Although this was not specifically investigated in our studies, it is unlikely that meaningful inhibition of these kinases occurred in vivo as the highest GNE-317 free brain concentration would not exceed 0.4 μmol/L (based on plasma and brain binding and data presented in Fig. 1B).

Studies in MDCK and LLC-PK cells overexpressing human or mouse P-gp or BCRP indicated that this compound was not a good substrate of these transporters (Table 1). These in vitro results suggest that GNE-317 brain penetration would not be markedly hindered were consistent with the data obtained in vivo. In mice, free brain concentrations achieved after a single 50 mg/kg oral dose were greater than the pAkt IC50 estimated in PC3 cells (0.034 μmol/L; Heffron and colleagues, manuscript in preparation) and led to strong pathway suppression for up to 6 hours postdose (Fig. 1B–D). It is worth noting that the brain-to-plasma ratio of unbound concentration was approximately 0.3 (Table 2) and similar at 1 and 6 hours postdose. This suggested that by 1 hour, a steady-state condition had been reached between brain and plasma and that the disappearance of GNE-317 from the brain paralleled its disappearance from plasma (Fig. 1B). For drug passively permeating the BBB, the equilibrium theory of free drug applies (25), and the ratio of unbound concentrations in the brain and plasma (Cbrain/Cplasma) is expected to equal (or approach) 1. For GNE-317, efflux at the BBB by transporters other than P-gp and Bcrp1 may explain the lower Cbrain/Cplasma experimental variability in the estimation of the free fraction in brain or plasma could also contribute to the calculation of this lower than expected free brain-to-plasma ratio. The in vitro determination of binding to brain homogenate has nevertheless been proposed as a reliable method to estimate free brain concentration (26). Despite this uncertainty on potential mechanisms still affecting its brain penetration, GNE-317 ability to cross the BBB constituted a remarkable improvement when compared with GDC-0941 and GDC-0980, PI3K, and PI3K/mTOR inhibitors, respectively (17, 18, 27), substrates of both P-gp and bcrp1, which did not cause any PI3K pathway modulation in intact brain (16, 19).

Numerous small molecule inhibitors targeting components of the PI3K signaling pathway (EGFR, PI3K, AKT, and mTOR) are being evaluated in GBM patients (28). However, most of them have been shown to be substrates of Pgp and/or BCRP (29–34), and are likely to exert their effects only in areas where the BBB or blood–tumor barrier is permeable, as described by Taskar and colleagues with lapatinib (35).

The marked inhibition of the PI3K pathway in the brain of mice with intact BBB (Fig. 1C), evidenced by the significant suppression of the PI3K and mTOR markers pAkt, p4EBP1, and pS6, suggested that GNE-317 could be efficacious in intracranial tumors driven by activation of this pathway. Studies in the U87 and GS2 orthotopic models of GBM showed that GNE-317 could reduce tumor volumes by 90% and 50%, respectively (Fig. 2). The U87 cells were selected as a well characterized and widely used glioma model (36, 37). However, in contrast to human GBM, this model presents an impaired BBB by DCE-MRI (Fig. 4E and F) despite very poor brain penetration in the presence of an intact BBB (16). Tumor penetration has also been observed with topotecan, (a substrate of P-gp and BCRP), which achieved a significantly higher unbound concentration in the U87 tumor than in the healthy contralateral brain (38). Hence, the effect observed with GNE-317, although promising and consistent with PI3K inhibition, was not unexpected and did not fully illustrate the greater potential of brain-penetrant compounds to reach the tumor. Thus, this model represents what might occur in contrast-enhancing region(s) of a brain tumor. Consistent with these findings, GDC-0941 was efficacious in this orthotopic model and able to reduce the tumor volume by more than 60% (Fig. 2C and D) despite very poor brain penetration in the presence of an intact BBB (16). Tumor penetration has also been observed with topotecan, (a substrate of P-gp and BCRP), which achieved a significantly higher unbound concentration in the U87 model versus complete lack of effect in the GS2 model further emphasizes the importance of brain penetration for optimal effect. For each compound, the concentrations were similar in the normal part of the brain and the tumored...
brain (Supplementary Table 2). This was consistent with the presence of an unaltered BBB; indeed, if the BBB in the GS2 model were disrupted, GDC-0941 and GDC-0980 concentrations would most likely be higher in the tumor-bearing side than in the normal brain, as reported for topotecan in the U87 model (38). In the GBM10 model, mice that were treated with GNE-317 experienced a marked survival benefit (Fig. 2E), indicating that GNE-317 was also efficacious in an in vivo-passaged xenograft model that had not been exposed to tissue culture conditions.

PI3K pathway suppression in the intracranial tumors, assessed by IHC, was consistent with the efficacy and BBB findings. GDC-0941, unable to cross an intact BBB, did not cause a noticeable change in pAkt staining in the GS2 tumor when compared with control, whereas the suppression of the pathway was marked following treatment with GNE-317 (Fig. 3A and C). In the U87 tumor, GDC-0941 did reduce the density and intensity of the pAkt staining (Fig. 3E) when compared with control (Fig. 3D), in agreement with its ability to cross the disrupted BBB of this tumor, whereas GNE-317 treatment led to the complete suppression of pAkt staining (Fig. 3F).

For all compounds tested, the brain-to-plasma ratios determined in the GS2 tumor-bearing mice at the end of study (Supplementary Table 2) were consistent with those obtained in CD-1 mice (Table 2) with GNE-317 after a single dose and, for GDC-0941, values were similar to what was previously described (16). The greater concentrations reached throughout the brain with GNE-317, when compared with GDC-0941 and GDC-0980, underscore the importance of efficient brain penetration to achieve efficacy in the presence of an intact BBB. These results clearly showed that although some compounds may be active in areas of brain tumors (primary or metastases) that have disrupted BBB and capture contrast agents, efficient antitumor activity on invasive areas with intact BBB requires compounds able to cross the BBB, such as GNE-317.

This report is, to our knowledge, the first describing the properties and efficacy of a PI3K inhibitor specifically designed to cross the BBB, with the treatment of GBM and possibly other PI3K-dependent CNS tumors as the primary objective. Although inhibition of PI3K may be associated with adverse effects, including ones related to the role of this pathway in glucose metabolism, this compound and potentially others optimized with the same purpose may provide a much needed treatment option for GBM. In addition, such brain-penetrant compounds, more likely to reach their target, should allow a more reliable assessment of biologic and pharmacodynamic hypotheses.

Disclosure of Potential Conflicts of Interest

J.N. Sarkaria is the recipient of a grant from Genentech, Inc. J.L. Pokorny reported no conflict of interest. No potential conflicts of interest were disclosed by other authors.

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Targeting the PI3K Pathway in the Brain—Efficacy of a PI3K Inhibitor Optimized to Cross the Blood–Brain Barrier

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