BAY 80-6946 Is a Highly Selective Intravenous PI3K Inhibitor with Potent p110α and p110δ Activities in Tumor Cell Lines and Xenograft Models

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Abstract

Because of the complexity derived from the existence of various phosphoinositide 3-kinase (PI3K) isoforms and their differential roles in cancers, development of PI3K inhibitors with differential pharmacologic and pharmacokinetic profiles would allow best exploration in different indications, combinations, and dosing regimens. Here, we report BAY 80-6946, a highly selective and potent pan-class I PI3K inhibitor with sub-nanomolar IC50 against PI3Kα and PI3Kδ. BAY 80-6946 exhibited preferential inhibition (about 10-fold) of AKT phosphorylation by PI3Kα compared with PI3Kδ in cells. BAY 80-6946 showed superior antitumor activity (>40-fold) in PIK3CA mutant and/or HER2 overexpression as compared with HER2-negative and wild-type PIK3CA breast cancer cell lines. In addition, BAY 80-6946 revealed potent activity to induce apoptosis in a subset of tumor cells with aberrant activation of PI3K as a single agent. In vivo, single intravenous administration of BAY 80-6946 exhibited higher exposure and prolonged inhibition of pAKT levels in tumors versus plasma. BAY 80-6946 is efficacious in tumors with activated PI3K when dosed either continuously or intermittently. Thus, BAY 80-6946 induced 100% complete tumor regression when dosed as a single agent every second day in rats bearing HER2-amplified and PIK3CA-mutated KPL4 breast tumors. In combination with paclitaxel, weekly dosing of BAY 80-6946 is sufficient to reach sustained response in all animals bearing patient-derived non–small cell lung cancer xenografts, despite a short plasma elimination half-life (1 hour) in mice. Thus, BAY 80-6946 is a promising agent with differential pharmacologic and pharmacokinetic properties for the treatment of PI3K-dependent human tumors.

Introduction

The phosphoinositide 3-kinase (PI3K) family generates 3'-phosphoinositides that activates a variety of cellular targets important for cell proliferation, survival, differentiation, and migration (1, 2). The class I PI3Ks transmit signals from receptor tyrosine kinases (RTK) and from the oncogenic protein Ras via the PI3Kα, β, or δ isoforms and from G protein–coupled receptors (GPCR) via the PI3Kβ or γ isoforms (3–5) Activation of PI3K has been directly linked to PI3K signaling and tumor growth that seems to be mediated via PI3Kβ isoform (10–12). In addition, overexpression or mutational activation of RTKs occurs in multiple tumor types, leading to increased PI3K signaling (13, 14).

Aberrant activation of class I PI3Ks has been associated with both intrinsic and acquired resistance to targeted agents, such as imatinib and trastuzumab (15–17), as well as to traditional chemo- and radiotherapy (18–21). The prototype PI3K inhibitors (e.g., LY294002) did not enter clinical development due to their lack of specificity and therapeutic window (22). A number of second generation selective PI3K or PI3K/mTOR inhibitors have entered early clinical development. However, clinical benefit has not yet been clearly shown in solid tumors. This is largely due to the complexity derived from the existence of various PI3K isoforms and their differential roles in cancer pathology and compensatory feedback activation of oncogenic pathways (23). As such, development of PI3K inhibitors with differential pharmacologic and pharmacokinetic profiles would allow best exploration in different indications, combinations, and dosing regimens to maximize the tumor-killing effects of PI3K inhibitors.

The present report explores the pharmacologic and pharmacokinetic profile of the intravenous PI3K inhibitor BAY 80-6946; E-mail: ningshu.liu@bayer.com

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BAY 80-6946, which preferentially inhibits PI3Kα and PI3Kδ and is highly potent in \textit{in vitro} and \textit{in vivo} preclinical tumor models with activated PI3K.

**Materials and Methods**

**Reagents and tumor cell lines**

BAY 80-6946 [2-amino-N-[7-methoxy-8-(3-morpholino propoxy)-2,3-dihydroimidazo[1,2-c]quinazolin]; Fig. 1A] was identified and synthesized at Bayer HealthCare Pharmaceuticals. The information about the reference compounds was described in Supplementary Fig. S1. For \textit{in vitro} studies, 5 mmol/L stock solution of BAY 80-6946 (in dimethyl sulfoxide with 10 mmol/L trifluoroacetic acid) was used. All tumor cell lines, except KPL4 cells, were obtained from the American Type Culture Collection; KPL4 cells were obtained from the laboratory of Dr. Junichi Kurebayashi (Kawasaki Medical School, Okayama, Japan). All cell lines were authenticated by
fingerprints at German Collection of Microorganisms and Cell Cultures (DSMZ) after two to four passages of the original stock from the providers. An aliquot of the substock was used for the studies described here. The cell lines were maintained in RPMI-1640 medium containing 10% heat-inactivated fetal calf serum.

Biochemical lipid kinase assays

The effect of BAY 80-6946 on PI3Kα, PI3Kβ, and PI3Kγ activity was measured by the inhibition of 32P incorporation into phosphatidylinositol as described in Supplementary Materials and Methods.

The effect of BAY 80-6946 on PI3Kα was determined by Upstate/Chemicon using their proprietary PIProfiler assay system that uses homogeneous time-resolved fluorescence to measure inhibition of kinase activity. The effect of BAY 80-6946 on PI4K-II, PIP2-5K, and PIPγ-4K was measured using assay conditions nearly identical to those for measuring PI3K activity, except that the p110 subunit was replaced with either recombinant PI4K-II protein or PIPγ-5K protein, respectively. In addition, PIPγ (Echelon) and PIPδ (Matreya) were used as the lipid substrate in place of phosphatidylinositol in the PIP2-5K and PIPγ-4K assays, respectively.

Assessment of pAKT and p-4E-BP1 levels

Levels of pAKT (T308), pAKT(S473), and p-4E-BP1 (T70) in the presence or absence of PI3K inhibitors were quantitatively determined using AlphaScreen SureFire assays (PerkinElmer) or by Western blot analyses. Briefly, the effects of PI3K inhibitors on the basal levels of pAKT and p-4E-BP1 in KPL4 cells were measured after 2 hours of treatment with PI3K inhibitors. To determine the inhibition of lysophosphatidic acid (LPA)–stimulated phosphorylation of AKT and 4E-BP1, PC3 cells were cultured in serum-free medium overnight, then incubated with PI3K inhibitors for 1 hour before being stimulated with 50 μmol/L LPA for 10 minutes. Determination of pAKT and p-4E-BP1 levels was conducted according to the manufacturer’s instructions.

Proliferation assays

Cell proliferation was determined using the CellTiter-Glo Luminescent Cell Viability Kit (Promega) as described in the Supplementary Data.

Apoptosis assays

BT-20 or BT474 breast tumor cells were treated with test compounds for 24 hours. Activation of caspase-9 was determined using the Caspase-Glo9 Assay Kit (Promega). Phosphorylation of p53 at Ser15 and PARP cleavage was measured using the MSD Apoptosis Kit (Cat # K15102D-2) at 48 hours after treatment.

Xenograft models

The in vivo antitumor efficacy of BAY 80-6946 was assessed in athymic nude rats or nude mice using xenograft models of human tumors. Animals were housed according to institutional guidelines with access to food (pelleted diet) and water ad libitum. Studies with patient-derived tumors were conducted in EPO GmbH or in Oncotest GmbH with written informed consent from each patient and the approval from local ethical committees. Tumor xenographs were generated by harvesting cells from mid-log phase cultures and injecting subcutaneously into the right flank of each rat and mouse. BAY 80-6946 was dissolved in a PEG400/acidified water (0.1 N HCl, pH 3.5; 20/80, v/v) or 5% mannitol vehicle. Treatment was initiated when all animals in an experiment had established tumors. BAY 80-6946 was administered every second day, every third day, or weekly via an intravenous bolus at the indicated doses. Tumor dimensions and body weights were recorded twice weekly starting on the first day of treatment. Tumor volumes were calculated using the equation \((l \times w^2)/2\), where \(l\) and \(w\) refer to the larger and smaller dimensions collected at each measurement. Antitumor efficacy was determined as a function of tumor growth inhibition (% TGI). TGI was calculated by the equation \([1 - (T/C)] \times 100\), where \(T\) and \(C\) represent the size of tumors in the treated (T) and control (C) groups, respectively. In addition, treatment responses were evaluated by means of clinically used Response Evaluation Criteria in Solid Tumors (RECIST) criteria; response rates (RR) were calculated as the percentage of animals with a complete or partial response (PR). The assessment of the pharmacodynamic effects of BAY 80-6946 in tumor specimens is described in the Supplementary Data.

Pharmacokinetics analysis

To determine the pharmacokinetic properties of BAY 80-6946, a solution of BAY 80-6946 was prepared in PEG400/pH 3.5 water (20/80) and administered as an intravenous bolus dose in the tail vein at 2 mL/kg for rats and 10 mL/kg for mice. Each time point has a group of 3 animals. Blood was collected at 5, 15, and 30 minutes and at 1, 4, 7, 24, and 30 hours after administration for pharmacokinetic analysis. Samples for tumor versus plasma exposure and pharmacodynamics biomarker analysis were taken at 24, 48, 72, and 96 hours.

Results

BAY 80-6946 is a highly selective and potent pan-class I PI3K inhibitor and does not exhibit significant cellular mTOR inhibition

BAY 80-6946 represents a novel proprietary imidazolinoquinazoline class of PI3K inhibitors identified through high-throughput screening of Bayer’s compound library and further optimized with respect to drug-like characteristics (Fig. 1A). BAY 80-6946 potently inhibited the catalytic activity of the class I PI3Kα, β, γ, and δ isoforms with IC50 values of 0.5, 3.7, 6.4, and 0.7 nmol/L, respectively. It showed significantly weaker activity against mTOR with an IC50 of 45 nmol/L. In contrast, 1 μmol/L BAY 80-6946 did not inhibit PI4K-II, PIP2-5K, PIPγ-4K, or an additional
inhibited LPA-stimulated AKT phosphorylation in PC3 was tested in KPL4 and PC3 cells. TGX-221 potently validated these assays, TGX-221, a PI3K
activity was measured using LPA-stimulated AKT phosphorylation in PTEN-null PC3 prostate tumor cells. To examine the cellular PI3K
isoform in mediating PTEN-deficient and GPCR signaling is essential for the signaling driven by
PI3K (24). KPL4, a breast carcinoma cell line that carries a
activating mutation and overexpresses HER2, was selected to assess the cellular PI3K activity against each individual isoform, the activity of
PIK3CA mutations
BAY 80-6946 in inhibition of PI3Kα- and PI3Kβ-mediated activation of downstream effectors of the pathway was examined. Previous studies have shown that p110α is essential for the signaling driven by PIK3CA mutations
and/or oncogenic RTKs, whereas p110β is the major isoform in mediating PTEN-deficient and GPCR signaling
(24). KPL4, a breast carcinoma cell line that carries a PIK3CA-activating mutation and overexpresses HER2, was selected to assess the cellular PI3Kα activity. PI3Kβ activity was measured using LPA-stimulated AKT phosphorylation in PTEN-null PC3 prostate tumor cells. To validate these assays, TGX-221, a PI3Kβ-specific inhibitor, was tested in KPL4 and PC3 cells. TGX-221 potently inhibited LPA-stimulated AKT phosphorylation in PC3 cells with single-digit nmol/L IC50 values, whereas it was completely inactive at 1 μmol/L in blocking AKT phosphorylation in KPL4 cells (Table 1). These data confirmed previous reports and validated the assays by showing that the phosphorylation of AKT in KPL4 cells is not driven by PI3Kβ, whereas LPA-stimulated AKT phosphorylation in PC3 cells is a PI3Kβ-dependent and PI3Kα-independent process (25). In KPL4 cells, BAY 80-6946 reduced basal levels of AKT phosphorylation at both Thr308 and Ser473 with IC50 values of 0.4 and 0.6 nmol/L, respectively (Table 1). BAY 80-6946 also reduced pAKT levels in PC3 cells with activity similar to that of TGX-221, albeit at seven to 20 times higher concentrations than those required in KPL4 cells. This is consistent with biochemical data showing that BAY 80-6946 inhibits both α and β PI3K isoforms, but is more potent against the α isoform. In line with this observation, BAY 80-6946 was also approximately 10 times more potent in blocking AKT phosphorylation in breast cancer cell lines with PIK3CA mutations (e.g., BT-20, BT-474, and KPL4) than in those with loss of PTEN (e.g., ZR-75-1, MDA-MB-468) assessed by Western blot analysis in Fig. 1D.

**Table 1.** Effect of BAY 80-6946 and comparators on phosphorylation of AKT and 4E-BP1 in KPL4 cells and LPA-stimulated PC3 cells

<table>
<thead>
<tr>
<th>Compound</th>
<th>IC50 (nmol/L) in KPL4</th>
<th>IC50 (nmol/L) in LPA-PC3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p-AKT (308)</td>
<td>p-AKT (473)</td>
</tr>
<tr>
<td>BAY 80-6946</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>GDC-0941</td>
<td>6.1</td>
<td>22</td>
</tr>
<tr>
<td>TGX-221</td>
<td>&gt;1,000</td>
<td>&gt;1,000</td>
</tr>
</tbody>
</table>

NOTE: Inhibition of cellular levels of phospho-AKT at S473, phospho-AKT at T308, and phospho-4E-BP1 at T70 by indicated PI3K inhibitors in KPL4- or LPA-stimulated PC3 cells was determined using AlphaScreen Kits from PerkinElmer.
BAY 80-6946. In contrast, there is no clear correlation between the sensitivity and loss of PTEN. In addition, BAY 80-6946 was active in inhibiting proliferation of tumor cell lines resistant to the anti-HER2 agents trastuzumab and lapatinib, such as T47D (PIK3CA-mut), ZR-75-1 (PTEN-null), and MCF7 (PIK3CA-mut) with IC50 values of 6, 24, and 27 nmol/L, respectively. The potent activity in hematologic tumor cell lines (PIK3CA wild-type) may associate with the potent PI3Kδ activity of BAY 80-6946. Taken altogether, these observations show that BAY 80-6946 has antiproliferative activity against a subset of human cancer cell lines, particularly those tumor cells with PI3K and/or
RTK alterations, such as PIK3CA mutation and/or overexpression of HER2 and may offer the potential to overcome resistance to anti-HER2 therapies.

**BAY 80-6946 induces apoptosis in a subset of tumor cell lines that are resistant to lapatinib and trastuzumab**

The PI3K/AKT pathway promotes tumor cell survival and prevents apoptosis by phosphorylation and inhibition of proapoptotic mediators such as caspase-9 and FOXO. BAY 80-6946 potently induced nuclear localization of FOXO1A with an EC_{0.5} less than 1 nmol/L (Supplementary Fig. S2) and apoptosis in a subset of tumor cell lines, including BT20, BT474, and ZR-75-1 breast cancer cells (26). To investigate the apoptosis pathways activated by BAY 80-6946, a set of studies were carried out with anti-HER2–resistant PIK3CA-mutated BT20 breast cancer cells. BAY 80-6946 significantly increased caspase-9 activities following 24-hour incubation with 2- and 3-fold inductions in caspase-9 activity at 20 and 62 nmol/L, respectively (Fig. 3A). These values were comparable with the IC_{50} of 6 nmol/L for antiproliferative activity in the same cell line. The effect of BAY 80-6946 on caspase-9 activation was even stronger than that of paclitaxel, whereas rapamycin was inactive at 1 μmol/L (Supplementary Fig. S3). Caspase-9 activation leads to cleavage of several procaspases, which in turn cleave cellular targets including PARP, thereby impairing DNA repair. DNA damage is reflected by the level of p53 phosphorylation at Ser15. Consistent with the induction in caspase-9, BAY 80-6946 at 200 nmol/L also increased levels of phosphorylated p53 at Ser15 (Fig. 3B) and cleaved PARP (Fig. 3C). Caspase-9 activation by BAY 80-6946, lapatinib or the combination of the two agents was further investigated in the anti-HER2–sensitive breast cancer cell line BT474. Interestingly, although lapatinib effectively inhibited tumor cell proliferation with an IC_{50} of 21 nmol/L (data not shown), it was incapable of inducing caspase-9 activation at a concentration up to 10 μmol/L (Supplementary Table S1). In contrast, BAY 80-6946 induced caspase-9 activation with an EC_{50} of 340 nmol/L. Interestingly, when BAY 80-6946 was combined with lapatinib, the same degree of caspase-9 activation could be reached with significantly less levels of BAY 80-6946 (e.g., 61 nmol/L) and lapatinib (e.g., 184 nmol/L) with combination indices of 0.20 to 0.29, across all concentrations tested (Supplementary Table S1). Taken together, these findings showed that BAY 80-6946, as a single agent, could induce cell death in both anti-HER2–sensitive and –resistant, PIK3-mutant breast tumor cells at clinically achievable concentrations (27). Combination with lapatinib further synergistically sensitized tumor cells to apoptosis.

**Preclinical pharmacokinetic and pharmacodynamic properties**

BAY 80-6946 has a high plasma-free fraction across all species tested (35% in rats, 14% in mice, 33% in dogs, and 16% in humans). The pharmacokinetic profile of BAY 80-6946 was evaluated following administration of single or multiple intravenous doses in nude rats (Supplementary Fig. S4). BAY 80-6946 exhibited very large volume of distribution (V_{ss} = 32 L/kg), high plasma clearance (3.95 L/kg h) and long T_{1/2} (6.0 hours). Similar exposure and other pharmacokinetic parameters were observed following multiple administration (every second day × 5), suggesting that there is no accumulation of compound or changes in metabolic processes. In comparison with the pharmacokinetic in rats, BAY 80-6946 had a higher plasma clearance (16 L/kg h) and a shorter T_{1/2} of 0.7 hours. The V_{ss} was large (12.9 L/kg) in mice (Supplementary Table S2).

To investigate pharmacokinetic/pharmacodynamic relationship, tumor samples were collected from nude rats bearing H460 human non–small cell lung carcinoma (NSCLC) xenografts and treated with a single 6 mg/kg i.v. bolus dose. The concentrations of BAY 80-6946 and pharmacodynamic markers in tumors were assessed. As shown in Fig. 4A, BAY 80-6946 levels were approximately 100-fold higher in the tumor than in plasma at 48 hours.
Figure 4. Pharmacokinetic/pharmacodynamic evaluations in H460 human NSCLC xenografts in nude rats. A, plasma and tumor concentrations of BAY 80-6946 formulated in PEG400/acidified water (0.1 N HCl, pH 3.5; 20/80, v/v) following a single intravenous administration of 6 mg/kg (3 animals/group). B, tumor pAKT (S473) levels following a single intravenous administration of BAY 80-6946 at 6 mg/kg (3 animals/group). C, pAKT staining (S473) at 24 hours after treatment with BAY 80-6946 and in untreated controls. D, Ki67 staining at 24 hours after treatment with BAY 80-6946 and in untreated controls. E, dose-dependent inhibition of FDG tumor uptake by BAY 80-6946. F, FDG-PET images before and after treatment with a single 6 mg/kg i.v. dose of BAY 80-6946.
tumor cells were arrested at the G0-phase of the cell cycle as indicated by phosphohistone H3 staining, respectively, showing 65% and 75% reduction in Ki67 and pAKT levels compared with vehicle for 24 hours after intravenous dosing and remained suppressed at 48 to 72 hours (Fig. 4B). Strong reduction of pAKT levels in tumors was observed as early as 1 hour after intravenous dosing (data not shown). The potent inhibition of tumor AKT phosphorylation correlates well with the high level of tumor uptake of FDG in a dose-dependent manner, with sustained inhibition evident over 24 to 48 hours after a single intravenous administration of 6 mg/kg (Fig. 4E and F). Taken together, these results suggest that in vivo, BAY 80-6946 reached high and prolonged exposure in tumors, which resulted in potent inhibition of the PI3K pathway exhibited by marked reduction in AKT phosphorylation and FDG uptake, as well as cell-cycle arrest in G0 in the H460 NSCLC xenograft model in rats.

**BAY 80-6946 is highly efficacious in rat and mouse tumor xenograft models following intravenous administration**

BAY 80-6946 was well tolerated at all doses and schedules tested in the studies described here without producing any lethality. The maximum-tolerated dose (MTD) in rats was defined as 6 mg/kg. At the MTD, a maximum mean body weight loss of 6% to 10% occurred during the first few days of dosing and then consistently returned to the normal range by the end of the dosing period. The MTD in mice was more than 14 mg/kg with a second day dosing schedule.

BAY 80-6946 was highly efficacious in a variety of human tumor xenograft models derived from different tumor indications that exhibit an activated PI3K pathway. The drug displayed robust antitumor activity in the rat KPL4 tumor xenograft model, which is an estrogen-independent HER2-positive breast carcinoma that carries a somatic PIK3CA mutation. BAY 80-6946 was administered at 0.5 to 6 mg/kg i.v. every second day for a total of five doses starting on day 14, following tumor cell implantation. On day 25, 3 days after the last dose, TGI rates of 57%, 74%, and 80% were observed with BAY 80-6946 at doses of 0.5, 1, 3, and 6 mg/kg, respectively (Fig. 5A). Complete tumor regression was shown in 10 of 10 rats in the 3 and 6 mg/kg groups, and all rats remained tumor free at the termination of the study on day 73. Tumor growth delays more than 25 days were observed in the 0.5 and 1 mg/kg dose groups.

Treatment of BAY 80-6946 led to tumor stasis in nude rats bearing HCT-116 human colon tumors, which carry PIK3CA and KRAS mutations. BAY 80-6946 was administered at 3 and 6 mg/kg i.v. every second day for a total of five doses, producing TGI of 75% and 88%, respectively, and tumor growth delays of 10 and 11 days, respectively (Fig. 5B, data not shown).

BAY 80-6946 was also effective in xenograft models established in nude mice with Lu7860 erlotinib-resistant, patient-derived NSCLC and MAXF1398 patient-derived luminal breast tumor models. BAY 80-6946 was administered at a dose of 14 mg/kg every second day for a total of 10 days, producing TGI rates of 88% in the NSCLC model (Fig. 5C) and 71% in the breast cancer model (Fig. 5D).

**Alternative dosing schedule of intravenous twice a day once weekly for BAY 80-6946 also shows antitumor activity**

The antitumor activity of BAY 80-6946 was also evaluated using a weekly dosing schedule, in which two doses of BAY 80-6946 were administered on the first day of the week. In the rat HCT-116 colorectal xenograft model, the TGI achieved with BAY 80-6946 at a dose of 9 mg/kg twice a day once weekly was equivalent to that with the 6 mg/kg dose given every second day for 10 doses (Fig. 6A). BAY 80-6946 at a dose of 6 mg/kg twice a day once weekly was efficacious with a TGI of 64%, comparable with the activity of docetaxel at 5 mg/kg every second day given for three doses.

Activation of PI3K has been shown to cause intrinsic and/or acquired resistance to chemotherapy. BAY 80-6946 was tested in combination with paclitaxel in Lu7343, a patient-derived PIK3CA (E545K)-mutated squamous cell NSCLC model in nude mice (Fig. 6B). Paclitaxel was given at doses of 15 or 25 mg/kg on days 14, 21, and 28. BAY 80-6946 was administered weekly at 10 mg/kg twice a day on days 15, 22, and 29 (24 hours after each paclitaxel dose). Treatment of BAY 80-6946 at 10 mg/kg/twice a day/week and paclitaxel at 15 mg/kg (60% of the MTD) alone showed only moderate efficacy with T/C% (treatment/control) values of 49% and 38%, respectively. Paclitaxel at the MTD (25 mg/kg) was effective and produced T/C% of 4% and 70% RR at the end of treatment on day 33 (Supplementary Table S3); however, tumor regrowth was observed immediately after stopping the treatment. Thus, on day 55, the RR in paclitaxel MTD group had dropped to 30% and tumors had progressed in 60% of the animals. The combination of BAY 80-6946 with both high and low doses of paclitaxel produced tumor regression, which was not only superior to either agent alone, but the combination with paclitaxel at the MTD also produced 100% RR with complete response (CR) in 5 of 10 and (PR) in 5/10 animals at the end of treatment. Importantly, in contrast with paclitaxel single agent at the MTD, the combination group showed a long-lasting tumor regression with 60% CR and...
40% PR on day 55 (22 days after stopping treatment). These findings suggest that BAY 80-6946, when combined with paclitaxel, synergistically improved tumor response rates and led to long lasting tumor regression even when dosed twice a day weekly over 3 weeks in mice.

Discussion

Many selective small-molecule inhibitors of PI3K have been identified, including selective pan-class I PI3K inhibitors, selective PI3Kδ inhibitors, and dual PI3K/mTOR inhibitors. These new PI3K inhibitors are currently in the early stages of clinical development. Several pan-class I PI3K inhibitors, including BKM120 and XL147, have entered phase II trials for various advanced malignancies, such as castration-resistant prostate, endometrial, and breast cancer, and a p110δ-selective PI3K inhibitor has entered phase III trials for lymphoma (28, 29). Although the pan-class I inhibitors have activity against each p110 isoform, they may show preferential activity for specific members. It is likely that the various PI3K isoforms play different roles based on tumor type, somatic mutations, and/or previous therapy, as well as different toxicology profiles; therefore, understanding the pharmacologic profile of each PI3K inhibitor may be important for developing PI3K therapeutics for specific malignancies. Here, we present BAY 80-6946, a highly selective and potent pan-class I PI3K inhibitor, which has preferential activity against the p110α and p110δ isoforms, compared with p110β and p110γ, based on biochemical assays and PI3Kα and PI3Kβ cellular assays. As it is difficult to compare the biochemical activity of the PI3K inhibitors against each p110 isoforms under physiologic conditions, we explored cellular assays in which the phosphorylation of AKT is driven by p110α or p110β, the two dominant isoforms expressed in solid tumors. The selectivity of BAY 80-6946 for the PI3Ks versus
mTOR was evident in both the biochemical and cellular assays: BAY 80-6946 was 90-fold more active against PI3Ka than against mTOR in biochemical assays and more than 250-fold more active in cellular assays using ELT3 cells with PI3K-independent constitutive activation of mTORC1 due to defective TSC2. This finding indicates that BAY 80-6946 is a highly selective and potent pan-class I PI3K inhibitor that does not exhibit significant cellular mTOR inhibition in contrast with BEZ-235 (30). In fact, based on the human pharmacokinetic data of BAY 80-6946, the plasma-free drug levels in human are significantly (>20-fold) below the concentration required for direct inhibition of mTOR kinase by BAY 80-6946 (27).

The greater activity of BAY 80-6946 against p110α versus p110β seen in the biochemical assays (IC50, 0.5 vs. 3.7 nmol/L) was confirmed in tumor cells. First, BAY 80-6946 was 16- to 20-fold more potent in inhibiting AKT phosphorylation in PIK3CA-mutated and HER2-overexpressing KPL4 cells (PI3Kα-driven p-AKT) compared with AKT phosphorylation in PTEN-null, LPA-stimulated PC3 cells (PI3Kβ-driven p-AKT). Second, BAY 80-6946 was about 10-fold more potent in inhibition of basal-level pAKT and p-p70S6K in cells with activated PI3Kα (such as BT20 and BT474) than in cells with loss of PTEN where PI3Kβ is activated (ZR-75-1 and MDA-MB-468; Table 1 and Fig. 1D). Interestingly, GDC-0941 showed equal potency in inhibition of cellular PI3Kα and PI3Kβ activities (Table 1). This result for GDC-0941 is in line with previous reports by O’Brien and colleagues (31)).

Profiling of BAY 86-6946 indicated that PIK3CA mutations and HER2 overexpression might be effective predictive biomarkers for predicting the sensitivity of breast tumor cells to BAY 80-6946. Thus, BAY 80-6946 had approximately 40 to 45 times greater antiproliferative activity against breast tumor cells with PIK3CA-activating mutations and/or HER2 overexpression than against those with HER2-negative tumors with wild-type PIK3CA (Fig. 2C). In contrast, the mean IC50 for GDC-0941 in PIK3CA-mutant and/or HER2-overexpressing cells compared with PIK3CA wild-type and HER2-negative cells showed only about a 2- to 3-fold difference in this study (data not shown) and in another report (31). The difference of the two pan-class I PI3K inhibitors in this aspect might be explained by the differential profiles in PI3K isoforms and kinase selectivity. BAY 80-6946 is a more potent PI3Kα inhibitor compared with GDC-0941, but GDC-0941 has equally potent activity against both PI3Kα and PI3Kβ. The higher sensitivity in cell lines harboring PIK3CA-activating mutations or amplification of HER2

Figure 6. Activity of BAY 80-6946 in xenograft models using a twice a day (BID) once-weekly schedule. BAY 80-6946 was formulated in 5% mannitol vehicle. A, HCT116 colon cancer xenografts in nude rats (8 rats/group). Tumor weight at the end of the treatment was measured and presented in median ± SEM. B, Lu7343 patient-derived NSCLC xenografts in nude mice (10 mice/group). Study was carried out in Epo GmbH. Tumor volume in median ± SEM is presented. Q2D, every second day.

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was also reported recently with the highly selective allo-
steric AKT inhibitor, MK-2206 (32). Hence, sufficient
selectivity against other kinases and potency in blocking
PI3Kα are indispensable for using PIK3CA and HER2 overexpression as potential predictive biomarkers
for PI3K pathway inhibitors.

Taken together, the differential isoform selectivity
observed with BAY 80-6946 and other investigational
PI3K inhibitors results in a differential antitumor profile
(as described above for BAY 80-6946 versus GDC-0941).
These findings suggest that the efficacy of the various
PI3K inhibitors may differ across tumors with different
genetic makeups. Understanding the preclinical profile
of each PI3K inhibitor may help to guide its clinical develop-
ment to the proper tumor type/subtype and also aid in
formulating an optimal biomarker strategy for identifying
patients most likely to benefit from treatment with a PI3K
pathway inhibitor with a certain isoform profile. On the
basis of these preclinical data, BAY 80-6946 was particu-
larly active in a subset of breast cancer, endometrial
cancer, and multiple myeloma cell lines, particularly
those with PIK3CA-activating mutations and/or HER2
overexpression (Fig. 2).

Of note, BAY 80-6946 also potently induced apoptosis in
BT20 human breast cancer cells with PIK3CA mutation
when it was tested as a single agent at a concentration
similar to the IC50 for blocking cell proliferation. A
detailed analysis of the molecular features for apoptosis
induction is described in another article (26).

BAY 80-6946 administered intravenously showed
potent antitumor activity in multiple cell-line-derived
and patient-derived xenograft tumor models. In line with
the in vitro cellular data, the greatest efficacy was seen in
xenograft models derived from tumor cells with PIK3CA
mutations or HER2 overexpression. In the HER2-activat-
ing PIK3CAmut KPL4 xenografts, BAY 80-6946 mono-
thrapy dosed intravenously at the MTD and 50% of MTD
(6 and 3 mg/kg every second day) produced complete
tumor regression that persisted after discontinuation of
therapy. To our knowledge, CR in 100% animals in this
model has not been achieved by any of to date investiga-
tional PI3K pathway inhibitors, including GDC-0941 (33),
CHS132799 (34), and MK-2206 (35), when they were dosed
at their respective MTD. BAY 80-6946 also exhibited
potent antitumor activity in HT116 colon cancer (Fig.
5B) and H460 NSCLC (data not shown) xenografts with
coeXisting PIK3CA and KRAS mutations, with complete
tumor stasis observed in these models. However, in these
models with KRAS mutations, it seems necessary to
administer BAY 80-6946 in combination with another
active agent, such as a MAP–ERK kinase (MEK) inhibitor,
to achieve tumor regression.

BAY 80-6946 exhibits unexpected higher and prolonged
exposure in tumors compared with plasma concentra-
tions after a single intravenous dose (Fig. 4A). It is plau-
sible that the higher exposure in tumors led to marked
and sustained reductions in tumor pAKT levels and FDG
uptake (lasting for at least 48 hours). Our initial data
comparing p-AKT inhibition in tumors versus in blood
monocytes indicated that BAY 80-6946 indeed suppressed
p-AKT in tumors with better potency and over a longer
time period (N. Liu; unpublished data). This result was
consistent with the antitumor activity seen in xenograft
models using a every second day schedule despite shorter
plasma T1/2 in rat (6 hours) and in mice (1 hour). Interest-
ingly, administration of BAY 80-6946 even on a twice a
day once-weekly schedule in HCT116 xenograft model in
rats resulted in a similar antitumor activity as the every
second day schedule. Furthermore, when BAY 80-6946
was combined with other agents, such as paclitaxel
(Fig. 6B), weekly dosing was sufficient to generate syner-
gistic antitumor effects and to induce complete tumor
regression in mice. This result indicated that maintaining
constant inhibition of PI3K pathway might not be
necessary especially when combining with paclitaxel.
Hence, intermittent combination with targeted and chemo
therapeutics could be a promising approach to synergis-
tically enhance the antitumor efficacy and meanwhile,
maintaining the safety profile in combination treatment.
Currently, a series of pharmacokinetic–pharmacodynamic
efficacy studies of tumor versus plasma and continuous
versus intermittent dosing schedules are being conducted.
These data will provide further insights to best explore
PI3K inhibitor BAY 80-6946 in clinical development.
On the basis of its antitumor profile and unique pharma-
cokinetic properties, BAY 80-6946 is currently being investi-
gated in phase I trials dosed weekly
intravenously in patients with advanced malignancies and in
combination with paclitaxel as well as with an allosterec
MEK inhibitor (36). Analysis of the upcoming clinical data
will provide further insights on how the PI3K isoform
profile together with pharmacokinetic properties impact
on the antitumor efficacy of BAY 80-6946 in the clinic.

Disclosure of Potential Conflicts of Interest
S.M. Wilhelm has ownership interest (including patents) in Bayer
HealthCare Pharmaceuticals. No potential conflicts of interest were
disclosed by the other authors.

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preparation of this manuscript, the key contributor of this work, Dr. Bruce Rowley passed away from NSCLC on July 16, 2013. Bruce was truly an intelligent, solid, and creative scientist. We will be missing him on our way towards developing effective therapeutics for cancer patients.

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