

Novel Inhibitors of Cyclin-Dependent Kinases Combat Hepatocellular Carcinoma without Inducing Chemoresistance

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Abstract

Treatment options for hepatocellular carcinoma using chemotherapeutics at intermediate and advanced stages of disease are limited as patients most rapidly escape from therapy and succumb to disease progression. Mechanisms of the hepatic xenobiotic metabolism are mostly involved in providing chemoresistance to therapeutic compounds. Given the fact that the aberrant activation of cyclin-dependent kinases (CDK) is frequently observed in hepatocellular carcinomas, we focused on the efficacy of the novel compounds BA-12 and BP-14 that antagonize CDK1/2/5/7 and CDK9. Inhibition of those CDKs in human hepatocellular carcinoma cell lines reduced the clonogenicity by arresting cells in S-G₂ and G₂-M phase of the cell cycle and inducing apoptosis. In contrast, primary human hepatocytes failed to show cytotoxicity and apoptosis. No loss of chemosensitivity was observed in hepatocellular carcinoma cells after long-term exposure to inhibitors. *In vivo*, treatment of xenografted human hepatocellular carcinomas with BA-12 or BP-14 effectively repressed tumor formation. Moreover, BA-12 or BP-14 significantly diminished diethylnitrosamine (DEN)-induced hepatoma development in mice. These data show that BA-12 or BP-14 exhibit strong antitumorigenic effects in the absence of chemoresistance, resulting in a superior efficacy compared with currently used chemotherapeutics in hepatocellular carcinomas. *Mol Cancer Ther*; 12(10); 1947–57. ©2013 AACR.

Introduction

Hepatocellular carcinoma (HCC) represents the sixth most common cancer and the third leading cause of cancer-related deaths worldwide (1). Less than 30% to 40% of patients with hepatocellular carcinomas are eligible for potentially curative therapies, including surgical resection and orthotopic liver transplantation due to advanced stages of disease at the time of diagnosis (2). As a result, patients with advanced hepatocellular carcinoma receive systemic chemotherapy. The use of chemotherapy is often

combined with transarterial chemoembolization (TACE), where the hepatic artery is obstructed (3). However, chemotherapeutic treatment of hepatocellular carcinoma most frequently associates with the increased expression of drug resistance genes, resulting in the insensitivity to available chemotherapeutic agents (4). Doxorubicin has shown inefficacy with a response rate of about 0% to 15% (5, 6), and other chemotherapy agents, such as epirubicin, cisplatin, 5-fluorouracil, etoposide, and their combinations, show even lower efficacies. For doxorubicin, one of the most important causes of chemoresistance is the increased expression of the ATP-binding cassette (ABC) transporters. Overexpression of the ABC member *ABCB1* (*MDR1*) encoding P-glycoprotein (P-gp) is associated with lower accumulation of doxorubicin in hepatocellular carcinoma cells and with a worse prognosis (7). Sorafenib represents the current treatment standard for advanced hepatocellular carcinoma by prolonging median survival of patients for about 3 months (8). These limitations in treatment modalities strongly indicate the urgent need for novel alternative treatment options.

Cyclin-dependent kinases (CDK) are fundamental for cell-cycle control and regulation of apoptosis (9, 10) and are found deregulated in most cancer cells. hepatocellular carcinoma shows frequent upregulation of CDKs through inactivation of CDK inhibitory proteins including p16^{Ink4},

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p21^{WAF1/CIP1}, p27^{KIP1}, and p57^{KIP2} as well as through increasing levels of cyclins (11, 12). In particular, CDK1 and CDK2 often show an aberrant regulation (13, 14). CDK2 provides S-phase entry by binding to cyclin E and allows S-phase progression by interacting with cyclin A (15). CDK1/cyclin A activity is essential for the initiation of prophase during the G₂-M transition (16). Interestingly, cyclin A was found to be overexpressed in 39% of hepatocellular carcinoma samples (17). Similarly, CDK1/cyclin B complexes participate and complete mitosis and cyclin B overexpression is frequently observed in hepatocellular carcinoma (18). Besides the fact that the sustained inhibition of CDK7 and CDK9 induces apoptosis (19), little is known about the deregulation of CDK5, CDK7, and CDK9 in hepatocellular carcinoma.

Thus, the targeting of CDKs has become an attractive approach in oncology (12). A multitude of small-molecule CDK inhibitors has been evaluated as promising antiproliferative agents for cancer therapy, including (R)-roscovitine (Seliciclib, CYC202). Roscovitine is known to selectively inhibit CDK1, CDK2, CDK5, CDK7, and CDK9 activities through its binding to the ATP-binding site (20). Currently, roscovitine is evaluated in a phase I clinical trial in combination with sapacitabine with patients suffering from advanced solid tumors (NCT00999401) and in a phase II trial from patients with non-small cell lung cancer (21). The effects of roscovitine and its derivatives vary according to cell type, but they are generally able to block the cell cycle at every position (22). The cell-cycle arrest is attributed to a direct inhibition of CDK1 and CDK2, whereas the induction of cell death by roscovitine is considered as a direct consequence of blocking the CDK7/CDK9-dependent transcription. CDK7 is an integral component of the transcription factor TFIIF (23), which phosphorylates the Ser5 in the C-terminal domain (CTD) of RNA polymerase II (Pol II) to facilitate transcription initiation. CDK9, a portion of the elongation factor P-TEFb (24), conducts a complementary function by phosphorylating Ser2 in the CTD of RNA Pol II, which is required for transcription elongation.

In this study, we investigated the molecular mechanisms of two novel roscovitine derivatives, designated BA-12 and BP-14, in hepatocellular carcinoma cells and further determined their anticancer activity in xenograft models and chemically induced hepatoma. We show that both compounds inhibit CDK1 and CDK2 on their own, leading to the arrest of hepatocellular carcinoma cells in S-G₂ and G₂-M. Moreover, BA-12 and BP-14 reduce the phosphorylation of RNA Pol II at Ser5 and Ser2 and selectively induce apoptosis of hepatocellular carcinoma cells rather than of primary human hepatocytes (PHH). Notably, no chemoresistance against these compounds could be observed after long-term treatment of hepatocellular carcinoma cells. *In vivo*, both BA-12 and BP-14 significantly diminished the growth of engrafted human hepatoma and were able to antagonize chemically induced liver cancer formation in mice.

Materials and Methods

Cell culture

The human hepatoma cell lines HepG2, PLC/PRF/5 (PLC), Hep3B, and 3sp (formerly described as HCC-1.1) were cultivated as described (25, 26). All cells were kept at 37°C and 5% CO₂ and were routinely screened for the absence of mycoplasma. The cell lines HepG2, PLC, and Hep3B were obtained from the American Type Culture Collection. The 3sp cells were established from a patient with hepatocellular carcinoma at the Medical University of Vienna (Vienna, Austria; ref. 26). All cell lines were verified by short-tandem repeat analysis in November 2012.

Primary human hepatocytes

Non-neoplastic tissue samples from liver resections were obtained from patients undergoing partial hepatectomy for metastatic liver tumors of colorectal cancer. Experimental procedures were conducted according to the guidelines of the charitable state controlled foundation HTCR (Human Tissue and Cell Research, Regensburg, Germany), with the informed patient's consent approved by the local ethical committee of the University of Regensburg. PHHs were isolated using a modified two-step EGTA/collagenase perfusion procedure as described previously (27). Viability of isolated PHHs was determined by trypan blue exclusion and cells with a viability of more than 85% were used for further work. Cells were plated on collagen-coated plates (BD Biosciences) at a density of 1.2×10^5 cells/cm². The medium consisted of Dulbecco's modified Eagle medium (DMEM) with 10% fetal calf serum (FCS), 2 mmol/L L-glutamine, 100 mg/mL streptomycin, 100 U/mL penicillin, and supplements as follows: 125 mU/mL insulin, 7.3 ng/mL glucagon, and 0.8 µg/mL hydrocortisone. Cells were incubated at 37°C in a humidified incubator with 5% CO₂ and media were changed daily.

Therapeutic agents

BA-12 (2-[[[2-[(4-aminocyclohexyl)amino]-9-cyclopentyl-purin-6-yl]amino]methyl]-4-chloro-phenol; Supplementary Fig. S1A) and BP-14 (N2-(4-aminocyclohexyl)-9-cyclopentyl-N6-[[6-(2-furyl)-3-pyridyl]methyl]purine-2,6-diamine; Supplementary Fig. S1B) were synthesized by procedures as described (28). Compounds were dissolved in dimethyl sulfoxide (DMSO). The stock solution of 100 mmol/L was diluted in assay buffer or in medium to concentrations indicated in the text. The maximum concentration of DMSO in the assays never exceeded 0.1%.

Determination of cell viability and inhibitory concentration

Cell viability was determined using the MTT assay. Briefly, cells were seeded in triplicates at a density of 6×10^3 cells per 96 wells. After 24 hours, cells were incubated with drug-containing medium for 72 hours. Cells were incubated with MTT solution (5 mg/mL; Sigma) and medium was replaced with DMSO after 5 hours. The

absorbance was measured at 620 nm by using a microplate reader (Asys HiTech). MTT assays were repeated three times for each drug application. IC₅₀ values were obtained by log-linear interpolation of data points and are depicted by dose-response curves using the software GraphPad Prism 5.01.

Kinase inhibition assays using cell-free extracts

Whole-cell extracts were prepared by lysing Hep3B cells with a buffer containing 20 mmol/L Tris pH 8.0, 100 mmol/L NaCl, 1 mmol/L EDTA, and 0.5% NP-40. Hundred micrograms of extract was used for immunoprecipitation at 4°C for 4 hours either with 1 µg of the anti-CDK2 antibody M2 (Santa Cruz Biotechnology) or with 1 µg of the anti-cyclin B1 antibody GNS1 (Santa Cruz Biotechnology). Precipitated protein was resuspended in 20 µL kinase buffer containing 5 µCi [γ -³²P]ATP (PerkinElmer), 1 µg histone 1 (New England Biolabs), and the respective concentration of inhibitor. After incubation for 60 minutes at 30°C, the supernatant was boiled in sample buffer and separated by SDS-PAGE. Proteins were transferred to nitrocellulose membranes and stained with Ponceau S before analysis by autoradiography.

Clonogenic survival assay

Five hundred cells were seeded in a 6-well plate and, either untreated or pretreated with BA-12 or BP-14 for 24 hours, incubated with standard medium for 10 days at 37°C and 5% CO₂. Colonies were fixed with methanol/acetic acid (3:1) and stained with 0.25% crystal violet. The crystal violet of fixed cells was solubilized with 1% SDS, and the absorbance was photometrically determined at 560 nm.

Cell proliferation analyzed by bromodeoxyuridine incorporation

Cultured cells were grown in medium containing 10 µmol/L bromodeoxyuridine (BrdUrd) for 1 hour. After removing labeling medium, cells were fixed and DNA denatured with a fixing/denaturing solution containing 2 mol/L HCl for 30 minutes at 37°C. To analyze BrdUrd incorporation *in vivo*, 200 µL Ringer solution containing 1 mg BrdUrd was intraperitoneally injected into xenografted mice 2 hours before sacrifice. Tumor tissue was fixed in 4% formaldehyde and processed for immunohistochemistry. BrdUrd incorporation was detected with a monoclonal anti-BrdUrd antibody (Sigma) and a peroxidase-conjugated secondary antibody (Calbiochem).

Flow cytometry

The analysis of cellular DNA content was conducted with a multicolor BD LSRFortessa cell analyzer (Becton Dickinson). Before the cytofluorometric measurement, about 5×10^5 cells were washed with PBS, fixed in 70% ethanol, washed again with PBS, and treated with 100 µg RNase A/50 µg propidium iodide per mL for 10 minutes to stain cellular DNA. The percentage of cells in the

various cell-cycle positions was calculated using a software package from the same manufacturer.

Determination of long-term chemosensitivity

Hepatoma cells were continuously cultivated in the presence of BA-12 or BP-14 at concentrations lower than the IC₅₀ (1:2 IC₅₀, 1:4 IC₅₀, 1:8 IC₅₀, and 1:16 IC₅₀). The selection of chemoresistant cells was monitored every 6 weeks for 9 months by the determination of IC₅₀ values using the MTT assay. Hepatocellular carcinoma cells showing higher IC₅₀ values after treatment with inhibitors than untreated cells are considered as chemoresistant.

Immunoblotting

Immunoblotting was conducted as described previously (29). Primary antibodies: anti-S807/811 Rb (Cell Signaling Technology), 1:500; anti-Rb (Cell Signaling Technology), 1:1,000; anti-phospho-Ser5 RNA Pol II (CDK7; Bethyl Laboratories), 1:1,000; anti-phospho-Ser2 RNA Pol II (CDK9; Bethyl Laboratories), 1:1,000; anti-RNA Pol II (Santa Cruz Biotechnology), 1:1,000; anti-PARP (Cell Signaling Technology), 1:1,000; anti-cleaved caspase-7 (Cell Signaling Technology), 1:1,000; anti-caspase-7 (Cell Signaling Technology), 1:1,000; anti-β-actin (Sigma), 1:2,500. Horseradish peroxidase-conjugated secondary antibodies (Calbiochem) were used at dilutions of 1:10,000.

Xenografted tumor formation and drug intervention

A total of 5×10^6 human hepatoma cells were resuspended in 100 µL Ringer solution and subcutaneously injected into severe combined immunodeficient (SCID) mice (Harlan Laboratories). Tumor volume was determined as described previously (29). Pharmacologic intervention was conducted in tumor-bearing mice for 17 days by daily intraperitoneal injection of either 5 mg/kg BA-12 or 1 mg/kg BP-14 in 100 µL of 0.01% DMSO. Control tumor-bearing mice received DMSO only. The experiments were carried out using 5 mice per group and carried out according to the Austrian guidelines for animal care and protection.

Diethylnitrosamine-induced liver cancer and drug intervention

To initiate tumor development in the liver, 14-day-old male C57BL/6J mice were intraperitoneally injected with a single dose of diethylnitrosamine (DEN, 25 mg/kg). After 8 months, pharmacologic intervention was administered in DEN-induced mice by 3 cycles of treatment with compounds for 10 days and a release from compounds for 7 days between the cycles. About 5 mg/kg BA-12 or 1 mg/kg BP-14 was intraperitoneally injected in 100 µL of 0.01% DMSO. Control mice received DMSO only. Thereafter, mice were sacrificed and livers were fixed in 4% formaldehyde. Two researchers (C. Haider and M. Grubinger) independently scored the diameters of neoplasia that could be monitored at the liver surface. Cancerous nodules with a diameter of up to 1 cm, covering more than 97% of all visible hepatomas, were included into the

analysis. The experiments were carried out using 20 mice per group and carried out according to the Austrian guidelines for animal care and protection.

Immunohistochemistry and TUNEL analysis

Mice were sacrificed and tumors were fixed as described (30). Four-micrometer-thick, paraffin-embedded sections were stained with anti-BrdUrd (Sigma), 1:200. Biotinylated secondary antibody was used at 1:200. The immunoperoxidase procedure was conducted using a Vectastain Elite ABC kit (Vector Laboratories) as described by the manufacturer. To detect DNA fragmentation by terminal deoxynucleotidyl transferase-mediated dUTP nick end labeling (TUNEL) analysis in tumor tissues, an *In Situ* Cell Death Detection kit (Roche) was used as recommended by the manufacturer.

Statistical analysis

Data were expressed as means \pm SD or SEM. The statistical significance of differences was evaluated using

an unpaired, nonparametric Student *t* test. Significant differences between experimental groups were *, $P < 0.05$; **, $P < 0.01$; or ***, $P < 0.005$.

Results

Cytotoxicity and kinase specificity of BA-12 and BP-14

Novel derivatives of roscovitine, designated BA-12 and BP-14, were synthesized on the basis of our knowledge of structure–activity relationships for roscovitine-related compounds (28, 31). Cell viability assays showed strong cytotoxic effects of BA-12 and BP-14 on human HepG2 and PLC hepatoma cells (Fig. 1A and B). Analysis of additional established hepatocellular carcinoma cell lines (Hep3B and 3sp) confirmed the cytotoxicity of BA-12 and BP-14 (Supplementary Fig. S2A and S2B). Dose–response curves revealed IC_{50} values below 1 $\mu\text{mol/L}$ for both compounds in the various hepatocellular carcinoma cell lines, reaching as low as 0.02 $\mu\text{mol/L}$ in PLC cells for

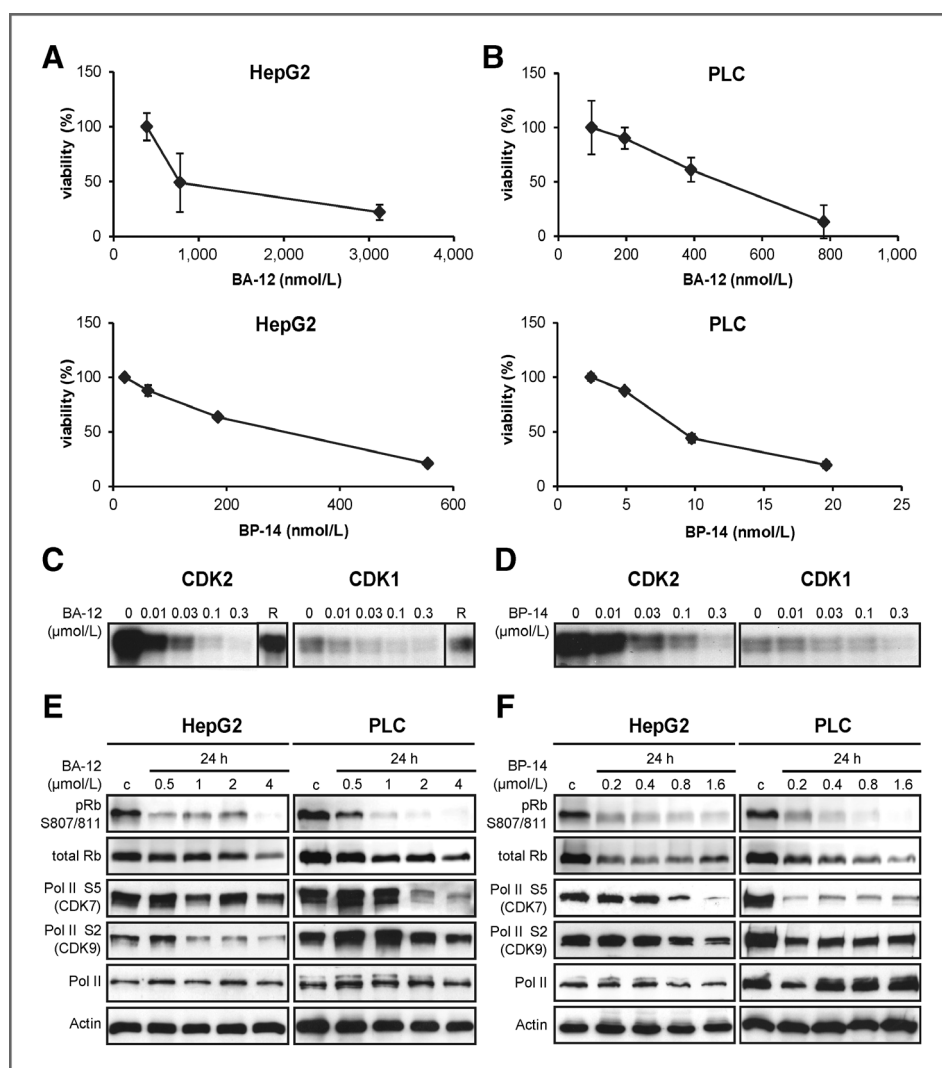


Figure 1. BA-12 and BP-14 diminish cell viability of hepatoma cells and block multiple CDKs. A and B, dose-dependent effects of BA-12 and BP-14 on the viability of human HepG2 (A) and PLC cells (B). C and D, inhibition of CDK1 and CDK2 activity by BA-12 (C) and BP-14 (D) in cell-free extracts. Roscovitine (R) was used at a concentration of 0.03 $\mu\text{mol/L}$. E and F, reduction of the CDK2-specific phosphorylation of Rb as well as suppression of CDK7 and CDK9 activity after exposure to different concentrations of BA-12 (E) and BP-14 (F) for 24 hours in HepG2 and PLC cells. As detected by immunoblotting, CDK7 and CDK9 activities correspond to serine 5 and serine 2 phosphorylation of RNA polymerase (Pol) II, respectively. The expression of actin indicates equal loading of protein samples. c, control. Error bars depict SD from at least three individual experiments.

BP-14 (Supplementary Table S1). Kinase assays using cell-free extracts showed that BA-12 or BP-14 significantly reduced CDK1/CDK2 activity at concentrations of 0.03 $\mu\text{mol/L}$ (Fig. 1C and D). Notably, roscovitine showed no effect at this concentration which suggests less potency than BA-12 and BP-14 (Fig. 1C). Furthermore, administration of HepG2 and PLC cells with 0.5 $\mu\text{mol/L}$ BA-12 or 0.2 $\mu\text{mol/L}$ BP-14, respectively, caused a significant decrease in CDK2-specific phosphorylation of retinoblastoma (Rb; Fig. 1E and F). This was associated with a more moderate lowering of total Rb levels at higher drug concentrations that might be due to apoptosis. In the same line, treatment of HepG2 and PLC cells with 1 and 2 $\mu\text{mol/L}$ BA-12, respectively, resulted in a more than 2.5-fold reduction of RNA polymerase II phosphorylation on serine 5 (CDK7) and serine 2 (CDK9; Fig. 1E and F), suggesting inhibition of CDK7/CDK9 activity. Administration of BP-14 below 1 $\mu\text{mol/L}$ led to a strong decrease of CDK7/CDK9 activity in HepG2 and PLC cells. Quantification of CDK inhibition using recombinant CDK substrates displayed IC_{50} values of BA-12 and BP-14 between 0.01 and 0.05 $\mu\text{mol/L}$ including antagonizing effects on CDK5 (Supplementary Table S2), thus corroborated the data obtained by cell-free extracts. Together, these results suggest that both BA-12 and BP-14 are highly potent cytotoxic compounds on hepatocellular carcinoma cell lines by the specific inhibition of CDK1/CDK2/CDK5/CDK7 and CDK9.

BA-12 and BP-14 abrogate clonogenicity and repress cell-cycle progression

We observed a more than 15-fold reduction of clonogenic growth behavior after treatment of HepG2 and PLC cells with 1 $\mu\text{mol/L}$ BA-12 (Fig. 2A). BP-14-treated cells displayed loss of clonogenicity even at 0.2 $\mu\text{mol/L}$ (Fig. 2B). Analysis of DNA synthesis revealed that treatment of HepG2 or PLC cells with 1 $\mu\text{mol/L}$ of either BA-12 or BP-14 decreased BrdUrd incorporation more than 2-fold as compared with control (Fig. 2C and D), indicating inhibition of DNA synthesis. Proliferation kinetics showed a cytostatic effect of BA-12 at 2 $\mu\text{mol/L}$ and of BP-14 at 0.8 $\mu\text{mol/L}$ in both HepG2 and PLC cells as well as in Hep3B hepatoma cells (Supplementary Fig. S3A and S3B). Accordingly, both compounds induced an accumulation in the G_2 -M and S- G_2 phase of the cell cycle (Fig. 2E and F). These data suggest that both BA-12 and BP-14 act antiproliferative by blocking DNA replication and by arresting hepatocellular carcinoma cells in the S- G_2 -M phase of the cell cycle.

BA-12 and BP-14 induce apoptosis in hepatoma cells rather than in PHHs

We next examined whether apoptosis is induced by BA-12 or BP-14 in HepG2 cells that harbor wild-type p53 and in PLC cells expressing full-length but mutated p53 (32). Administration of 1 $\mu\text{mol/L}$ BA-12 induced cleavage of PARP and p53 expression in HepG2 cells (Fig. 3A, left). Comparable observations were made after treatment with

2 $\mu\text{mol/L}$ BA-12 in p53-mutated PLC cells (Fig. 3A, right). BP-14 was able to trigger PARP cleavage even at a concentration of 0.2 $\mu\text{mol/L}$ (Fig. 3B), thus being more potent to induce apoptosis as compared with BA-12. Cleavage of caspase-7 further confirmed data of PARP processing (Fig. 3A and B). As BP-14 induced apoptosis at 0.2 $\mu\text{mol/L}$ in the absence of CDK7/9 inhibition, these data suggest cytotoxic effects that are also independent of CDK7/9. Yet, both BA-12 and BP-14 failed to induce PARP processing in PHHs, which are the cellular origin of hepatoma (Fig. 3C and D). Accordingly, both BA-12 and BP-14 exhibited IC_{50} values of 26 and 20 $\mu\text{mol/L}$ in PHHs, respectively, which was 35-fold (BA-12) or 160-fold (BP-14) higher than observed in HepG2 cells (Supplementary Table S1). From these data, we conclude that the novel CDK inhibitors induce apoptosis of hepatocellular carcinoma cells at low concentration in a p53-independent fashion and fail to execute cytotoxic effects in PHHs.

Long-term cytotoxicity of BA-12 and BP-14 in hepatocellular carcinoma cells

Most of the chemotherapeutic compounds that are currently available for hepatocellular carcinoma treatment show low cytotoxic efficacy presumably due to the modification and rapid removal from neoplastic hepatocytes by mechanisms of induced multiple drug resistance (33). This poses one of the major problems in combating liver cancer. Therefore, we analyzed whether BA-12 and BP-14 display changes in cytotoxicity by treating hepatoma cells at concentrations half of their IC_{50} values as well as at serial dilutions (1:2 IC_{50} , 1:4 IC_{50} , 1:8 IC_{50} , and 1:16 IC_{50}) for up to 9 months. In case, hepatocellular carcinoma cells lower their chemosensitivity by acquiring a resistance mechanism, IC_{50} values increase over time. Most notably, we observed that IC_{50} values were maintained in hepatoma cells as compared with control during sustained drug exposure (Table 1). These data provide strong evidence that the cytotoxic effects of BA-12 and BP-14 on hepatocellular carcinoma cells are maintained upon persistent drug treatment, suggesting that hepatoma cells fail to acquire chemoresistance toward BA-12 and BP-14.

In vivo application of BA-12 and BP-14: inhibition of xenografts and DEN-induced hepatoma

To examine antitumorigenic effects of BA-12 and BP-14 *in vivo*, we assessed hepatoma xenograft models derived from HepG2 and PLC cells. Tumor-bearing mice were injected either with BA-12 or BP-14 at maximum-tolerated doses (MTD). Xenografted mice well tolerated the treatment regimen of BA-12 and BP-14 as 100% of mice survived until the end of drug application. Administration of BA-12 or BP-14 resulted in reduced tumor volumes and tumor stasis of xenografts. Both were effective in the PLC as well as in the HepG2 model (Fig. 4A and B). Interestingly, BP-14 exhibited a higher potency than BA-12 in the PLC model resulting in a more pronounced reduction of the tumor volume. Evaluation of S-phase-positive cells in HepG2- and PLC-derived tumors by BrdUrd incorporation into

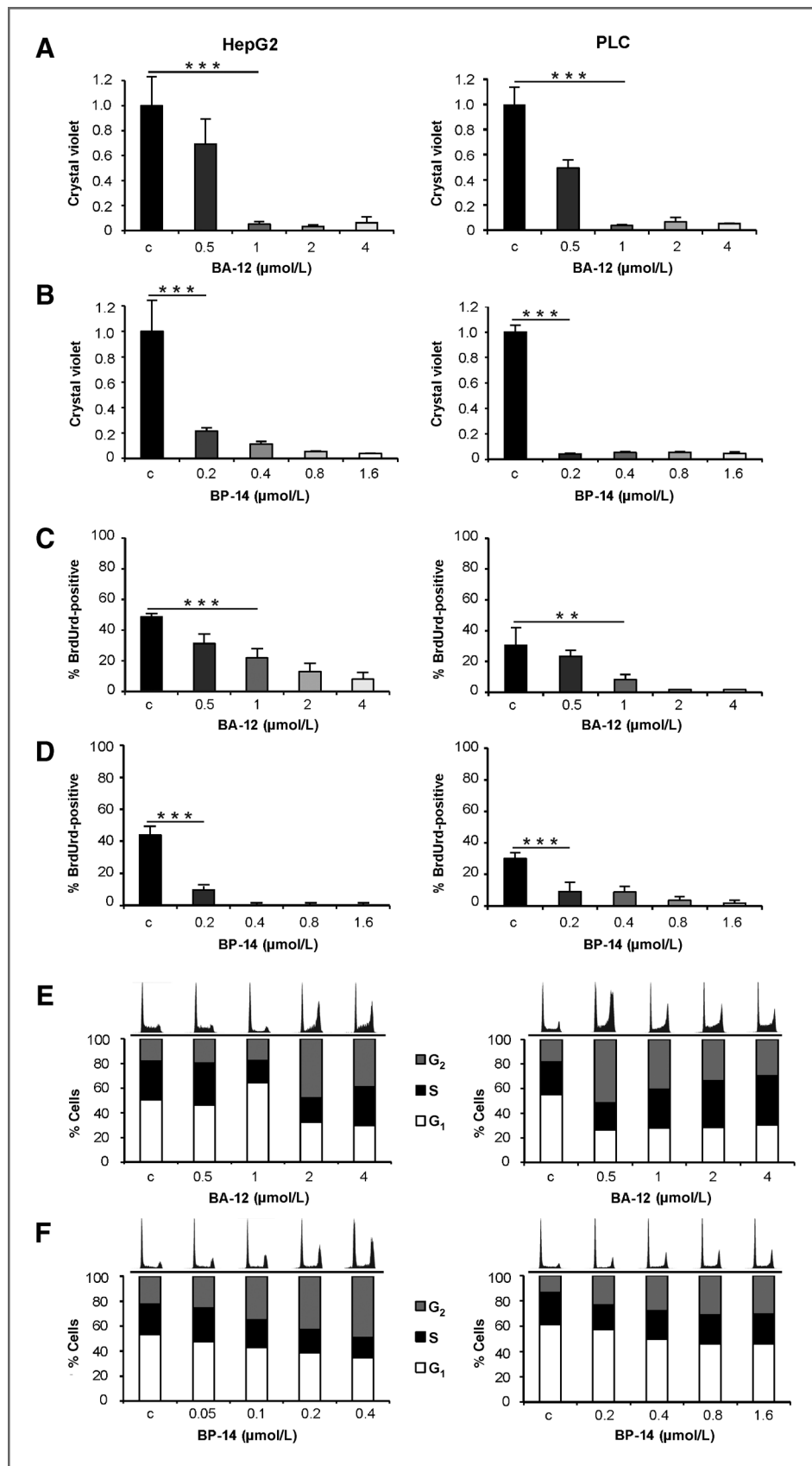
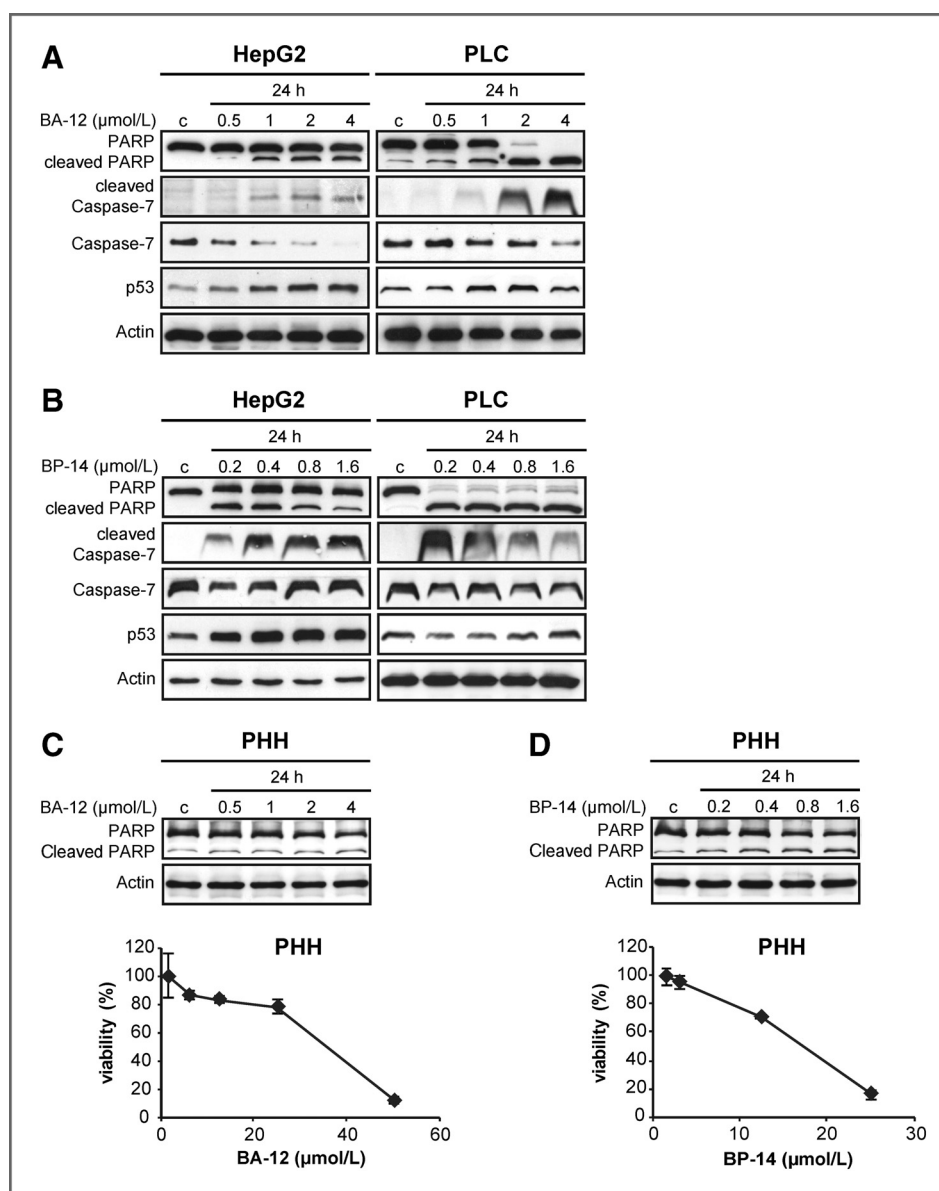


Figure 2. BA-12 and BP-14 interfere with clonogenicity and cell-cycle progression of hepatocellular carcinoma cells. A and B, quantitative evaluation of crystal violet-positive colonies generated from HepG2 (left) and PLC cells (right). Cells were pretreated with different concentrations of BA-12 (A) or BP-14 (B). C and D, HepG2 (left) and PLC cells (right) were exposed to BA-12 (C) or BP-14 (D) for 24 hours and the DNA synthesis analyzed by BrdUrd incorporation. E and F, flow cytometry showing the cell-cycle distribution of HepG2 (left) and PLC cells (right) after treatment with different concentrations of BA-12 (E) or BP-14 (F) for 24 hours. The cellular DNA content is shown in histograms (top) and the percentage of cells in G₁, S-, or G₂ phase are depicted in bars after quantification (bottom). c, control. Error bars depict SD from at least 3 individual experiments. Statistical significance is indicated with asterisks (**, $P < 0.01$; ***, $P < 0.005$).

Figure 3. Apoptosis induced by BA-12 and BP-14 in hepatocellular carcinoma cells but not in PHHs. A and B, cleavage of PARP and caspase-7 after treatment of HepG2 and PLC cells with different concentrations of BA-12 (A) or BP-14 (B) for 24 hours. C, PARP cleavage (top) and determination of dose-dependent effects of BA-12 on the viability (bottom) of PHHs. D, PARP cleavage and viability of PHHs after treatment with BP-14. Actin is shown as loading control. Error bars depict SD from at least 3 individual experiments.



DNA revealed an up to 2-fold decrease after exposure to either BA-12 or BP-14 (Fig. 4C and D). Further analysis showed a 2-fold increase of TUNEL-positive cells after

Table 1. Sustained cytotoxicity in hepatocellular carcinoma cell lines after long-term exposure to BA-12 and BP-14

	BA-12		BP-14	
	HepG2	Hep3B	HepG2	Hep3B
c, μmol/L	0.81	0.64	0.11	0.12
1/2 IC ₅₀ , μmol/L	0.99	0.29	0.11	0.17
1/4 IC ₅₀ , μmol/L	0.87	0.32	0.16	0.21
1/8 IC ₅₀ , μmol/L	0.80	0.24	0.09	0.08
1/16 IC ₅₀ , μmol/L	0.99	0.35	0.06	0.07

treatment of HepG2-derived tumors with BA-12 or BP-14, which was similar in PLC tumors, indicating that both compounds induce apoptosis in tumor tissues (Fig. 4E and F). Thus, cytostatic effects by reduced DNA synthesis and cytotoxic effects by augmented apoptosis explain the efficacy of these compounds.

We further analyzed the ability of BA-12 and BP-14 to interfere with endogenous liver cancer development that was chemically induced by the hepatotoxin DEN. Treatment modalities of DEN-induced mice included three cycles of treatment at MTDs of BA-12 and BP-14 for 10 days with interim breaks of 7 days (Fig. 5A). Evaluation of tumor nodules that are observed on the surface of cancerous livers revealed that BA-12 causes a 1.4-fold decrease of tumor nodules size as compared with control mice. Intervention with BP-14 showed comparable anticancer

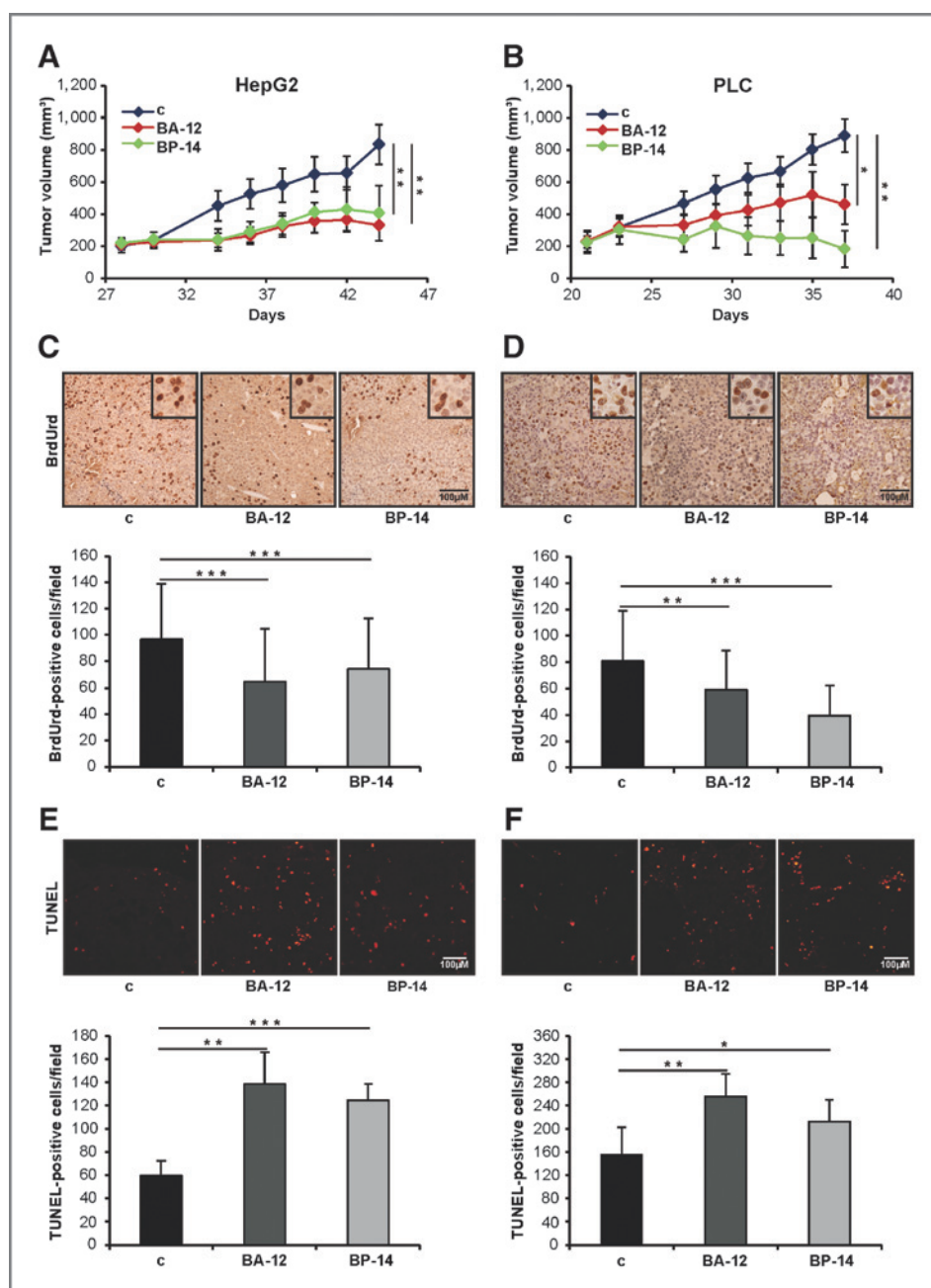


Figure 4. Intervention of xenografted hepatocellular carcinoma models with BA-12 and BP-14. Tumors were generated by subcutaneous injections of HepG2 and PLC cells into immunodeficient SCID mice. Pharmacologic intervention was conducted in tumor-bearing mice by daily intraperitoneal injection of either BA-12 or BP-14 for 17 days. A and B, volumes of HepG2- (A) and PLC-derived tumors (B) in the absence of compounds (control) and after interference with BA-12 or BP-14. C and D, immunohistochemistry showing tumor sections stained with anti-BrdUrd antibody. Insets show BrdUrd labeling at higher magnification. The panel below shows quantitative analysis of BrdUrd incorporation. c, control. E and F, TUNEL-positive cells in tumor sections and the respective quantitative analysis. Error bars depict SD and SEM from 3 individual experiments that were carried out in quadruplicates. Statistical significance is indicated with asterisks (*, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.005$).

effects by a 1.3-fold decline of DEN-induced hepatoma (Fig. 5B and C). Noteworthy, mice treated with BA-12 and BP-14 did not show a decrease in body weight compared with control group (Fig. 5D), suggesting that both compounds do not show obvious side effects. In summary, these data indicate that both BA-12 and BP-14 exhibit strong antihepatoma activities *in vivo* as observed in xenograft models as well as in endogenous liver cancer.

Discussion

A considerable number of small-molecule inhibitors of CDKs have been designed to block proliferation of cancer

cells (34). Inhibitors of the first generation include roscovitine, a 2,6,9-tri-substituted purine derived from studies evaluating the structure-activity relationship of this compound class (20, 35). It is a selective inhibitor of CDK1/cyclin B, CDK2/cyclin E, CDK5/p35, CDK7/cyclin H, and CDK9/cyclin T1. In this study, we assessed the anticancer activities of the novel roscovitine derivatives BA-12 and BP-14 in hepatoma. These compounds show a much higher potency than roscovitine as indicated by the inhibition of CDK1/2 in cell-free extracts (Fig. 1C) and through considerably lower IC_{50} values against recombinant CDK1, 2, 5, 7 and 9 (compare Supplementary

Figure 5. BA-12 or BP-14 reduce DEN-induced hepatoma formation. Endogenous liver cancer was induced by a single DEN injection in 14 day-old male C57BL/6J mice. **A**, scheme depicting the treatment schedule with BA-12 or BP-14. After 8 months (hatched box), DEN-induced mice were subjected to 3 cycles of drug treatment for 10 days (green boxes) and a release from compound for 7 days between the cycles. **B**, representative morphologies of DEN-induced hepatoma (control) and those treated with BA-12 and BP-14. White circles indicate cancerous liver nodules in the left lateral liver lobe. **C**, diameters of cancerous nodules were scored on the surface of livers and depicted in bars. Statistical significance is indicated with asterisks (*, $P < 0.05$). **D**, effect of drug treatment on mouse body weight. Groups of mice were weighed after the 3 cycles of drug treatment and mean weights are depicted in bars.

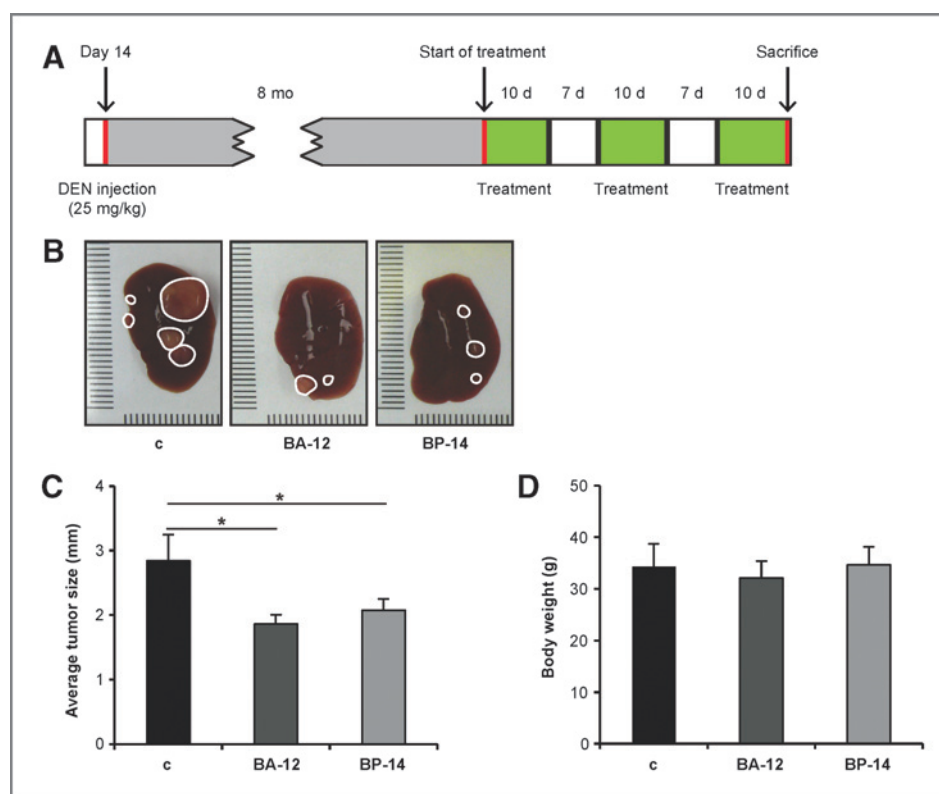


Table S2; with Table 1 in ref. 31), suggesting an ameliorated selectivity against these kinases. The kinase selectivity of both BA-12 and BP-14 to CDKs was verified on a panel of 110 human protein kinases (E. Řezníčková, manuscript in preparation). Besides CDKs, the most sensitive kinases are CK1d and ERK8. In addition, BA-12 also targets CLK2.

Nowadays the standard treatment of unresectable, intermediate stages of hepatocellular carcinoma is TACE. Several chemotherapeutics are used of which doxorubicin and cisplatin are most commonly used (36). Compared with doxorubicin, BA-12 shows a similar IC_{50} on hepatoma cell lines, whereas BP-14 shows a 10-fold higher efficacy (26). Cisplatin displays an even 10- to 20-fold lower ability of inhibition. The major problem with current chemotherapeutic drugs is that chemoresistance frequently occurs in hepatocellular carcinoma therapy. Recently, Ye and colleagues described that repeated doses of doxorubicin lead to an overexpression of P-gp and MRP1 and to a subsequent loss of doxorubicin accumulation, thus making cells less susceptible to treatment already after a short period of drug exposure (33). In contrast, our results show that BA-12 and BP-14 fail to trigger resistance mechanisms in various hepatoma cell lines. Hepatocellular carcinoma cells did not exhibit enhanced viability even after long-term treatment. In addition, both compounds were tested using a panel of chemosensitive tumor cell lines and their chemoresistant sublines overexpressing ABCB1. The P-gp-overexpressing sublines showed a lower sensitivity against BA-12

and BP-14 by showing IC_{50} values, which were 2-fold higher than in parental cells (data not shown). Thus, these data propose BA-12 and BP-14 as substrates of P-gp. In agreement, several studies showed that roscovitine represents a high-affinity substrate of P-gp as well, yet no concomitant ABCB1-mediated resistance could be observed after treatment with roscovitine (26). Noteworthy, roscovitine was also shown to induce apoptosis in a doxorubicin-resistant human myeloma cell line that overexpresses P-gp (37). Therefore, we speculate that despite being P-gp substrates, BA-12 and BP-14 do not induce resistance and are thus being promising novel therapeutic agents with persistent antihepatoma activities. BA-12 and BP-14 might be superior to currently available chemotherapeutics but should be used as first line therapy due to the frequent upregulation of P-gp in drug-treated patients with hepatocellular carcinoma.

Roscovitine is effective in antagonizing CDKs before its processing by either glucuronidation or cytochrome P450-mediated metabolism. The cytochromes P450 CYP3A4 and CYP2B6 generate the carboxylate PMF30-128 as major metabolite that lacks inhibitory function on CDKs (38). Glucuronidation takes place via the UDP-glucuronosyltransferases (UGT) 1A1, 1A3, and 2B7 (38, 39). Although not tested yet, we assume that BA-12 and BP-14 are metabolized in a similar way. Currently running experiments focus on the uptake and metabolism of these drugs and investigate whether the compound clearance via 1A1, 1A3, and 2B7 is much more reduced as compared with roscovitine. We further hypothesize that glucuronidation

might be the cause for the higher potency of BP-14 as compared with BA-12. BA-12 harbors a hydroxyl group that gets oxidized to glucuronic acid and is thus much more water soluble leading to a more rapid elimination from the body. The faster metabolic clearance of BA-12 might explain the 10-fold difference in IC_{50} values between BA-12 and BP-14.

HepG2 cells represent a widely used hepatocellular model in pharmacologic studies, as these malignant hepatocytes are well-differentiated and show features of normal parenchymal liver cells such as secretion of lipoproteins, biosynthesis of multiple plasma proteins, and plasma membrane polarity (40, 41). However, HepG2 cells show lower levels of CYPs and UDP-glucuronosyl-transferases (42), when compared with PHHs. Therefore, we treated PHHs with compounds and showed via determination of their IC_{50} values that BA-12 and BP-14 are cytotoxic in PHHs at about 35- and 160-fold higher levels as compared with hepatoma cell lines, respectively. Notably, both compounds are not capable to induce apoptosis of PHHs suggesting lack of obvious adverse effects of BA-12 and BP-14 due to the high xenobiotic metabolism under physiologic conditions.

BA-12 and BP-14 display further anticancer activities as pilot experiments revealed. Both compounds are able to reduce cell invasion and migration of 3-dimensional hepatospheres into the surrounding extracellular matrix (data not shown). In accordance with these findings, CDK7 was found to affect the migration of ovarian, breast, melanoma, and prostate cancer cell lines (43). In the same line, CDK9 was shown to be involved in cancer cell invasion, as miR-34a suppresses the assembly of the CDK9-c-Myc-P-TEFb complexes, leading to an inhibition of cell migration and invasion (44). CDK9 further induces TNF- α -mediated expression of MMP-9 that facilitates tumor dissemination (45). In addition, inhibition of CDK5 is suggested to be beneficial for anticancer therapy as CDK 5 stimulates Rac1-dependent migration of endothelial cells during tumor angiogen-

esis (46). The putative multiple inhibitory roles of BA-12 and BP-14 in hepatoma growth and migration make them promising new drugs that must be considered for clinical investigation.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): C. Haider, M. Grubinger, W. Miklos, W. Berger, W. Mikulits

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Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): T.C. Weiss, M. Zatloukal, T. Gucký

Study supervision: M. Strnad, W. Mikulits

Other: Synthesis of CDK inhibitor BA-12, M. Zatloukal; Synthesis of studied compounds, T. Gucký

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