Preclinical Therapeutic Efficacy of a Novel Pharmacologic Inducer of Apoptosis in Malignant Peripheral Nerve Sheath Tumors

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Abstract
Neurofibromatosis type I (NF1) is an autosomal disorder that affects neural crest-derived tissues, leading to a wide spectrum of clinical presentations. Patients commonly present with plexiform neurofibromas, benign but debilitating growths that can transform into malignant peripheral nerve sheath tumors (MPNST), a main cause of mortality. Currently, surgery is the primary course of treatment for MPNST, but with the limitation that these tumors are highly invasive. Radiotherapy is another treatment option, but is undesirable because it can induce additional mutations. Patients with MPNST may also receive doxorubicin as therapy, but this DNA-intercalating agent has relatively low tumor specificity and limited efficacy. In this study, we exploited a robust genetically engineered mouse model of MPNST that recapitulates human NF1-associated MPNST to identify a novel small chemical compound that inhibits tumor cell growth. Compound 21 (Cpd21) inhibits growth of all available in vitro models of MPNST and human MPNST cell lines, while remaining nontoxic to normally dividing Schwann cells or mouse embryonic fibroblasts. We show that this compound delays the cell cycle and leads to cellular apoptosis. Moreover, Cpd21 can reduce MPNST burden in a mouse allograft model, underscoring the compound’s potential as a novel chemotherapeutic agent. Cancer Res; 74(2); 586–97. ©2013 AACR.

Introduction
Neurofibromatosis type I (NF1) is an autosomal dominant genetic disorder that affects 1 in 3,500 people (1). Patients typically present with a constellation of signs, including café-au-lait pigmentation spots, benign neurofibromas, axillary or inguinal freckling, optic gliomas, Lisch nodules in the eye, bone abnormalities, and multiple additional less penetrant manifestations (2). Furthermore, NF1 patients are predisposed to malignant peripheral nerve sheath tumors (MPNST; ref. 3), which are a significant source of mortality.

Neurofibromas are benign tumors that grow on the skin (dermal) or inside the body (plexiform; ref. 4). Neurofibromas have complex cellularity, including Schwann lineage cells, fibroblasts, perineurial cells, mast cells, collagen deposits, and physical proximity to peripheral nerves. Plexiform neurofibromas appear in 30% of NF1 patients (5), and although they retain the capacity to enlarge throughout life, many lines of evidence point to an embryonic origin (6). Dermal neurofibromas can arise from a type of adult stem cell called skin-derived precursors (SKP; ref. 4), whereas plexiform neurofibromas arise from embryonic neural crest lineage Schwann cell progenitors (6). Whether the two cell types are related or the same remains unclear (7).

NF1 patients can also develop malignant tumors, including leukemia, rhabdomyosarcoma, and neuroblastoma in children (2). The most common malignancy, however, is MPNST, which arises from and appears in, approximately 9% to 21% of patients with plexiform neurofibromas (8). MPNSTs are initially difficult to detect, metastasize widely, and have a poor prognosis (9). Mutation of NF1, which encodes a RAS-GTPase activating enzyme (10), is known to activate RAS downstream effectors, including the ERK, PI3K, and mTOR pathways (11–15). The two most common cancer-associated mutations present in MPNSTs in addition to NF1 mutation are the tumor suppressors p53 (16–18) and CDKN2 (16, 19–23). Mice harboring mutated NF1 and p53 or NF1 and CDKN2 spontaneously develop MPNST (24, 25). In addition to NF1 and its downstream effector Ras, the conditional deletion of Pten also leads to MPNST in mice (26).

In this study, we exploit a robust model of MPNST that histologically and molecularly recapitulates human MPNST. We used primary cells from these MPNSTs to screen for compounds that specifically arrest tumor cell growth. Such compounds would not only have potential as a platform for novel therapeutic development but also for probing the biology of MPNST. Elucidating the mechanism of action of such compounds could identify MPNST specific pathways and point to therapeutic opportunities. We report a novel small
molecule, compound 21 (Cpd21 or identification number SW106065), which induces apoptosis in all models of MPNST tested but spares normal cells and tissues. Moreover, we demonstrate that this compound can decrease the tumor burden of MPNST in a mouse allograft model.

Materials and Methods

Cell and tissue samples
S462 and SN96.2 cells were a gift from Karen Cichowski. Schwann cells (ScienCell) were cultured in Schwann Cell Medium (ScienCell) and were immortalized with Myc-retrovirus (27).

High-throughput screening
sMPNST and Schwann cells (400 cells/well) were seeded in 384-well plates and grown overnight. Compounds (final concentration of 2.5 μmol/L) were added and incubated for 96 hours. CellTiter-Glo (Promega) was added and luminescence was quantified using Envision 2102 Multilabel Reader (Perkin Elmer).

Soft agar assay
Acellular layer of 0.6% Bacto-agar in MPNST media was plated. Cells were trypsinized, pelleted, resuspended, mixed in 1:1 ratio with 0.6% agar to a final density of 1 × 10^5 cells/mL, and plated on top. After incubation for 10 days, colonies were stained with 0.5 mL 0.005% crystal violet.

Cell-cycle analysis
Cells were collected, trypsinized, and lysed with 600 μL lysis buffer (0.01 mol/L Hepes/NaOH (pH 7.4), 0.14 mol/L NaCl, 2.5 mmol/L CaCl2), and incubated with 50 μL 0.5% Tween 20/1%BSA/PBS, 20 μL anti-BrdU-FITC (BD Biosciences), and 5 μL of 10 mg/mL RNase overnight. Samples were pelleted, resuspended in 1 mL 5 μg/mL propidium iodide (Sigma), and analyzed by flow cytometry.

Western blotting
Cells were collected, trypsinized, and lysed with 600 μL radioimmunoprecipitation assay buffer. Samples were run on 5%–20% SDS-PAGE gel (Bio-Rad). The following primary antibodies were used: Cyclin D1, H3 (Millipore), Caspase-3, pERK, pAKT, AKT (Cell Signaling Technology), PARP (Novus Biologicals and Millipore), α-Tubulin ( Sigma), and GAPDH (Santa Cruz).

Annexin V staining
Floating and adherent cells were resuspended in binding buffer (0.01 mol/L Hepes/NaOH (pH 7.4), 0.14 mol/L NaCl, 2.5 mmol/L CaCl2), and processed according to manufacturer (MACS Miltenyi Biotec). Three hundred microliters of suspension was added to 5 μL Annexin V antibody (MACS Miltenyi Biotec) and 2.5 μL propidium iodide, and analyzed by flow cytometry.

Metabolic stability studies
Cpd21 levels for metabolic stability and pharmacokinetic studies were monitored by liquid chromatography (LC/MS-MS) with AB/Sciex (Applied Biosystems) 3200 Qtrap mass spectrometer coupled to Shimadzu Prominence LC. Cpd21 was detected with the mass spectrometer in positive MRM (multiple reaction monitoring) mode by following the precursor to fragment ion transition 205.0 to 111.1. An Agilent C18 XDB 5 μm packing column (50 × 4.6 mm) was used for chromatography. For S9 studies, Cpd21 (2 μmol/L) was incubated in a 1 mL incubation volume with 1 mg of murine CD-1 S9 (combined cytosol and microsome) fractions (Celsius/In Vitro Technologies) and phase I (the NADPH regenerating system) cofactors (Sigma) for 0 to 240 minutes. Reactions were quenched by mixing the incubation mixture with 1 mL of methanol/0.2 ng/μL n-benzylbenzamide/0.2% formic acid. The quenched mixture was vortexed for 15 seconds, incubated at room temperature for 10 minutes, and spun for 5 minutes at 986 × g. Supernatants were spun in a refrigerated microcentrifuge for 5 minutes at 16,100 × g. The second supernatant was transferred to an HPLC vial and analyzed by LC/MS-MS.

Pharmacokinetic studies
Six- to 7-week-old NCR-nu/nu female mice were implanted with 2.5 × 10^5 MPNST cells in the left flank, subcutaneously. When tumors reached 800 mm^3, animals were injected with Cpd21 at 20 mg/kg in 0.2 mL 10% ethanol, 10% PEG400, 80% of a solution of 5% dextrose, pH 7.4. Blood was drawn at 0, 10, 30, 60, 180, 360, and 1,440 minutes using the anticoagulant, ACD (acidified citrate dextrose) and plasma isolated by centrifugation. One hundred microliters of plasma was mixed with 200 μL acetonitrile containing 0.15% formic acid and 37.5 ng/mL n-benzylbenzamide IS. Samples were vortexed 15 seconds, incubated at room temperature for 10 minutes, and spun twice at 16,100 × g at 4°C. Amount of Cpd21 present in plasma was quantified by LC/MS-MS to determine the rate of clearance from mouse blood. A Cpd21 standard curve was generated using blank plasma spiked with known Cpd21 concentrations and processed as described above. Concentrations of Cpd21in each time-point sample were quantified using Analyst 1.4.2. The limit of detection was defined as 3-fold above the signal obtained from blank plasma. The limit of quantitation (LOQ) was defined as the lowest concentration at which back calculation yielded a concentration within 20% of theoretical. The LOQ for plasma was 5 ng/mL and 1 ng/mL for tumor. Back calculation of points on the standard curve yielded values within 15% of theoretical over 4 orders of magnitude (5,000 to 5 ng/mL). Pharmacokinetic parameters were calculated using the noncompartmental analysis tool of WinNonLin (Pharsight).

Bioluminescent imaging
sMPNST-luc½ cells (2 × 10^5 cells/200 μL) were injected in both flanks of nude mice. Mice were injected with 40 mg/kg Cpd21 or vehicle (10% ethanol, 10% PEG400, and 80% of 5% dextrose in water) intraperitoneally twice per day for 4 weeks. Mice were injected with 160 μL 20 mg/mL β-Luciferin Potassium Salt (Perkin Elmer) in 0.9% sterile NaCl, and total flux was quantified using IVIS Lumina II (Caliper Life Sciences) weekly.
Immunohistochemistry

Tissues were fixed in 10% formalin and paraffin embedded. After sectioning, immunohistochemical studies were performed as previously described (29). The following primary antibodies were used: S100 (28), GAP43 (Abcam), Ki67 (Thermo Scientific), Caspase-3 (Cell Signaling Technology), and PARP (Novus Biologicals).

Results

Nf1 and p53-deficient SKPs form MPNST

Nf1-associated dermal and plexiform neurofibromas are histologically compatible despite having significantly different natural history and tumor progression properties. Recently, we reported that SKPs are the cell-of-origin of dermal neurofibromas (4). Given the potential in mice for neural crest progenitors to give rise to MPNST after additional loss of the p53 tumor suppressor, we tested the consequences of dual Nf1 and p53 loss of function (NP) in SKPs. SKPs from mice with Nf1<sup>f/f</sup>p53<sup>f/f</sup> genotype were cultured and infected with adenovirus containing Cre-GFP (Ad-Cre) to induce tumor suppressor recombination (Fig. 1A, a). Infected SKPs were screened for expression of GFP and genotyped for the deletion of Nf1<sup>b</sup> (Lane 1, Nf1<sup>+/+</sup> control. Lane 2, wild-type Nf1<sup>+/+</sup> control. Lanes 3 and 4, Nf1<sup>−/−</sup> SKPs that were infected with Ad-Cre-GFP. These Nf1<sup>−/−</sup>p53<sup>−/−</sup> SKPs were then autologously transplanted back into the original mouse (c). Resultant tumors were transplanted into nude mice via xenotransplantation (d). qRT-PCR results (e). Lanes 1–4, MPNSTs derived from cis-Nf1<sup>−/−</sup>p53<sup>−/−</sup> mice. Lanes 5–7, MPNSTs derived from PLP-CreERT-Nf1<sup>−/−</sup>p53<sup>−/−</sup> mice that had been injected with tamoxifen to induce recombination. Lanes 8–11, sMPNSTs. B, a, hematoxylin and eosin staining of sMPNST. Immunohistochemical staining for S100B in sMPNST (b) and skin (c), and for GAP43 in sMPNST (d) and skin (e). Scale bars, 100 μm.

Figure 1. MPNSTs can be generated from SKPs that are deficient in Nf1 and p53. A, SKPs were isolated from the skin of cis-Nf1<sup>+/f</sup>p53<sup>+/f</sup> mice, cultured, and infected with Ad-Cre-GFP (a). Infected SKPs were screened for expression of GFP and genotyped for the deletion of Nf1<sup>b</sup> (Lane 1, Nf1<sup>+/+</sup> control. Lane 2, wild-type Nf1<sup>+/+</sup> control. Lanes 3 and 4, Nf1<sup>−/−</sup> SKPs that were infected with Ad-Cre-GFP. These Nf1<sup>−/−</sup>p53<sup>−/−</sup> SKPs were then autologously transplanted back into the original mouse (c). Resultant tumors were transplanted into nude mice via xenotransplantation (d). qRT-PCR results (e). Lanes 1–4, MPNSTs derived from cis-Nf1<sup>−/−</sup>-p53<sup>−/−</sup> mice. Lanes 5–7, MPNSTs derived from PLP-CreERT-Nf1<sup>−/−</sup>p53<sup>−/−</sup> mice that had been injected with tamoxifen to induce recombination. Lanes 8–11, sMPNSTs. B, a, hematoxylin and eosin staining of sMPNST. Immunohistochemical staining for S100B in sMPNST (b) and skin (c), and for GAP43 in sMPNST (d) and skin (e). Scale bars, 100 μm.

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Figure 2. Identification of Cpd21 by high-throughput, small-molecule screening and validation. A, summary of screening procedure. B, high-throughput screening data for sMPNST cells (top) and Schwann cells (bottom). Intensity of blue or red signal correlates with degree of inhibition or induction of ATP levels by small molecules, respectively. C, structure of Cpd21. D, dose-response curves of Cpd21 (0.125, 0.25, 0.5, 1, 2.5, 5, 10, and 20 μmol/L) in sMPNST cells, MEF, Schwann cells, and MPNST cells from multiple murine models. E and F, dose-response curves of Cpd21 treatment on human MPNST cell lines, S462 and SNF96.2, respectively, compared with mouse NIH3T3 cells and sMPNST cells. G, dose-response curves of Cpd21 treatment on wild-type Schwann cells, compared with sMPNST and MPNST from cis-NF1+/−;p53+/− mice. H, soft agar assay of Cpd21-treated (0.25, 0.5, 1, 2.5, or 5 μmol/L) sMPNST cells compared with DMSO. Arrows indicate colonies, which may be out of plane in agar. Scale bars, 100 μm. J, soft agar assay of MPNST cells from cis-NF1−/−;p53+/− mice and that were treated with DMSO or Cpd21 at 0.25, 0.5, 1, 2.5, or 5 μmol/L. Arrows indicate colonies, which may be out of plane in agar. Scale bars, 100 μm. K, quantification of J. All values, mean ± SD. The Student t test used for significance testing (*, P < 0.05; **, P < 0.01; ***, P < 0.001).
data demonstrated expression of all markers in all sMPNSTs analyzed (Fig. 1Ae). Thus, sMPNSTs exhibit molecular characteristics of human NF1 associated MPNST.

Hematoxylin and eosin (H&E) staining of sMPNSTs showed presence of spindle-shaped cells that interweave in a poorly differentiated, wavy appearance, reminiscent of human MPNST histology (Fig. 1B, a). In addition, the commonly used MPNST markers, S100 and GAP43, were present (Fig. 1B—b—e). Therefore, our results indicate that SKPs, cells that give rise to neurofibromas upon loss of Nf1, can also give rise to MPNST with additional loss of p53. The facility of generating and explanting sMPNSTs made this a favorable system for performing chemical compound screens.

Novel MPNST inhibitory small molecule

We hold the concern that over time in culture, tumor cells will drift from their original intrinsic cellular and molecular programs in unpredictable ways. These uncontrollable and unmeasurable changes may inadvertently alter fundamental properties of the original tumor cells. To mitigate these concerns, the relative facility of generating primary cultures from sMPNSTs afforded the advantage of propagating sufficient numbers of cells for a high-throughput screening while keeping the cell passage number low. We performed a limited high-throughput, small-molecule screen using sMPNST cells produced above in an extension of a related ongoing large-scale screen in our research group. We carried out a 200,000 compound screen on primary mouse glioblastoma multiforme cells that are deficient for Nf1, p53, and Pten (S. Kyun Lim and Luis F. Parada, unpublished data). This original glioblastoma multiforme screen yielded 4,480 compounds, identified as inhibitory to glioblastoma multiforme cell growth. We reasoned that since sMPNST cells are deficient in two of these same tumor suppressors, some compounds might have conserved sMPNST cell growth inhibitory properties.

A well-established luminescence assay for measuring ATP levels (an indication of cellular metabolic activity) was adopted (CellTiter-Glo, Promega), and performed 96 hours after compound exposure. A total of 1,515 compounds exhibited more than 20% decrease in ATP levels at 2.5 μmol/L (Fig. 2A and B). To exclude compounds that exert general cell toxicity, or perturb the generic cell cycle or mitotic machinery, we counter-screened the 1,515 compounds against Myc-immortalized Schwann cells (27, 36) and eliminated compounds that showed more than 20% lower ATP levels. The resultant 119 compounds were rescreened on sMPNSTs with a cutoff at 70% inhibition. Twenty-eight compounds passed this test and were further tested in dose response studies ranging from 125 nmol/L to 20 μmol/L. The twenty-first compound (Fig. 2C; Cpd21 or SW106065) inhibited ATP consumption of sMPNST and all other models of MPNST tested (Fig. 2D) with an EC50 of 1 μmol/L. The twenty-first compound (Fig. 2C; Cpd21 or SW106065) inhibited ATP consumption of sMPNST and all other models of MPNST tested (Fig. 2D) with an EC50 of 1 μmol/L. The twenty-first compound (Fig. 2C; Cpd21 or SW106065) inhibited ATP consumption of sMPNST and all other models of MPNST tested (Fig. 2D) with an EC50 of 1 μmol/L. We extended the functional analysis of Cpd21 to additional cell lines. Human MPNST cell lines, S462 (Fig. 2E) and SNF96.2 (Fig. 2F), were assayed for dose-dependent growth, and EC50 concentrations of 439.0 and 753.6 nmol/L, respectively, were determined. In contrast, NIH3T3 cells and wild-type...
Schwann cells showed a considerably higher dose resistance (Fig. 2G). We also tested sMPNST response to Cpd21 in anchor-age-independent soft agar growth assays and found that Cpd21 inhibited colony formation (Fig. 2H and I). This effect was also observed in MPNST cells derived from\textit{cis-Nf1}\textsuperscript{+/-}\textit{p53}\textsuperscript{+/-}\textit{C0} mice (Fig. 2J and K). Thus, Cpd21 has general toxic activity on \textit{Nf1} and \textit{p53}-deficient MPNST cells but not on diverse nontumorigenic, mitotically active fibroblasts or Schwann cells.

**Cpd21 delays the cell cycle in sMPNST**

To address the mechanism of action of Cpd21, we treated sMPNST cells at 0.25, 0.5, 1, 2.5, and 5 \(\mu\)mol/L for 24 hours, and pulsed with BrdUrd for 30 minutes. Subsequent flow cytometry analysis revealed a decreased percentage of cells in S-phase, and a corresponding increased percentage in G1–G0 and G2–M, compared with treatment with DMSO alone (Fig. 3A).

Several cell-cycle regulatory genes exhibited decreased mRNA in the presence of Cpd21, including \textit{cyclin A2}, \textit{cyclin B1}, \textit{cyclin D1}, \textit{cyclin E}, \textit{cdk4}, and \textit{cdk6} (Fig. 3B and C). Increased levels of \textit{cdk6} were observed in a dose-dependent manner (Fig. 3D). Also, levels of \textit{cyclin D1} protein, which is known to interact with cdk4/6 in regulating G1–S progression, were decreased (Fig. 3E; refs. 37, 38). These results indicate that following Cpd21 exposure, cells in S-phase are underrepresented, consistent with cell-cycle delay and an arrest of the mitotic machinery.

We examined Cpd21-treated sMPNST cells for apoptosis by Annexin V-FITC–conjugated flow cytometry. Tumor cells treated with Cpd21 concentrations at or above 0.5 \(\mu\)mol/L showed a statistically significant increase in the percentage of apoptotic cells (Fig. 4A). At the EC\textsubscript{50} concentration of 1 \(\mu\)mol/L, 11.23 ± 1.56\% of the cells were Annexin V-positive, compared with 5.02 ± 0.83\% in DMSO-treated control cells.

We also performed Western blotting of Cpd21-treated sMPNST cells and observed caspase-3 (Fig. 4B) and PARP (Fig. 4C) cleavage, consistent with induced apoptosis. We further validated this mechanism in MPNST cells cultured from spontaneous MPNSTs from our \textit{cis-Nf1}\textsuperscript{+/-}\textit{p53}\textsuperscript{+/-}\textit{C0} mouse model (Fig. 4D), and in the human MPNST cell line, S462 (Fig. 4E). Other cell types, including \textit{Myc}-immortalized Schwann cells (Fig. 4F) and MEF cells (Fig. 4G), did not undergo caspase-3 cleavage. Together, these data indicate that, \textit{in vitro}, Cpd21...
induced mitotic arrest of MPNST cells that ultimately results in cellular apoptosis, and that this phenotype was not observed in untransformed dividing cells.

**Cpd21 decreases tumor burden and induces apoptosis in vivo**

To determine whether Cpd21 could be directly tested in vivo, we sought to define the pharmacologic properties in vitro according to previously published methods (39, 40). To examine stability, Cpd21 was incubated with purified, hepatic, enzymatic S9 fraction over a period of 2-40 minutes, and measured over time (Fig. 5A). The half-life in the S9 fraction is 22.65 minutes. We also incubated Cpd21 with cultured hepatocytes and found that the half-life is 121.6 minutes (Fig. 5B). These assays demonstrate that Cpd21 would have reasonable stability in vivo.

We next sought to define the pharmacokinetic properties of Cpd21 according to previously published methods (40). sMPNST (2.5 × 10⁵) cells were injected subcutaneously into nude mice, and when tumors reached 800 mm³, a single dose of Cpd21 was injected intraperitoneally at 20 mg/kg. Plasma and tumor samples were collected after 10, 30, 90, 180, 360, and 960 minutes and assayed by mass spectrometry (Fig. 5C). We observed that Cpd21 rapidly distributes from the plasma into sMPNST tissues and that the half-life in sMPNST tissues is 6 to 8 hours once the compound is completely distributed. Importantly, Cpd21 concentration remains above the EC50 concentration of 1 μmol/L (204 ng/mL) in the sMPNSTs for more than 6 hours. These results indicate that Cpd21 is successfully delivered to the tumor tissue in adequate concentrations and with an adequate half-life for in vivo studies.

We next determined a dose tolerable for chronic in vivo administration of Cpd21. Cpd21 dissolved in a mixture of ethanol, PEG400, and dextrose was delivered intraperitoneally at 20 or 40 mg/kg twice per day, into nude mice over the course of 2 weeks for comparison with vehicle administration. These concentrations were selected because 40 mg/kg is the maximum solubility in the aforementioned formulation. Over this period, the mice were weighed daily and observed for signs of toxicity. Neither concentration of Cpd21 produced measurable weight loss or distress in the mice (data not shown). Therefore, we selected 40 mg/kg twice per day intraperitoneally as the dosing regimen for efficacy studies.

We then tested the effects of Cpd21 administration on tumor burden in vivo. Nude mice were injected with sMPNST cells carrying a luciferase gene (MPNST-luc+) to permit noninvasive in vivo tumor growth assessment by luminescence. One week after allograft, recipient mice were intraperitoneally injected with either 40 mg/kg of Cpd21 or vehicle twice daily over 4 weeks, and mice were imaged weekly. We observed that treatment with Cpd21 reduced the tumor burden as measured by total flux normalized to baseline flux levels (Fig. 5D and E). BrdUrd was injected into mice before necropsy. Both BrdUrd and Ki67 evaluation indicated a significant decrease in tumor cell proliferation following Cpd21 treatment (Fig. 5F–I). These results are consistent with our observations that Cpd21 inhibits the cell cycle in vitro, resulting in a decrease in the proliferative capacity of sMPNSTs.

Consistent with in vitro data, Cpd21-treated sMPNSTs exhibited elevated activated caspase-3 and PARP (Fig. 5J–M). These results were confirmed by Western blotting to detect cleaved caspase-3 and PARP in tumors from our in vivo model (Fig. 5N). Taken together, our results demonstrate that Cpd21 can be delivered to mice in concentrations to sufficiently penetrate sMPNST tissue, and inhibit tumor development.

To extend the previous observation that chronic Cpd21 exposure did not appear to cause general toxicity, we examined various tissues following necropsy for histologic evidence of Cpd21-induced toxicity. In addition to tumor tissue (Fig. 6A), we examined liver (Fig. 6B), kidney (Fig. 6C), brain (Fig. 6D), skin (Fig. 6E), and sciatic nerve (Fig. 6F), and found no evidence of abnormal histology. Activated caspase-3 could only be detected in tumor samples (Fig. 6G) and not in other tissues examined (Fig. 6H–L). In contrast to other chemotherapeutic agents such as doxorubicin that induce toxicity in a variety of tissues (41), Cpd21 appears to act most notably on malignant tumor tissue.

**Interaction with other anticancer agents**

In addition to doxorubicin, MPNSTs have been shown to be sensitive to pathway-specific inhibitors of MAPK/ERK (42), PI3K/AKT (43), mTOR (43–45), and CXCR4 (7). We therefore examined whether Cpd21 in conjunction with doxorubicin or specific inhibitors, including U0126, a MEK inhibitor (42); LY294002, an AKT inhibitor (43); rapamycin, an mTOR inhibitor (43–45); and AMD3100, a CXCR4 inhibitor (7), might better inhibit sMPNST cell growth as assessed by ATP consumption (46). We found the inhibition of the PI3K pathway combined with Cpd21 treatment resulted in a decrease in cellular growth and survival that is greater than either inhibitor alone (Fig. 7A and B). Phospho-AKT Western blots of sMPNST cells treated with LY294002 at 20 μmol/L for 30 or 60 minutes verified effective pAKT inhibition in sMPNST cells (Fig. 7C). Inhibition of the MEK/ERK pathway combined with Cpd21 treatment did not produce detectable additive or synergistic effects (Fig. 7D). Phospho-ERK inhibition by U0126 was verified by Western blotting (Fig. 7E). Inhibition of the mTOR pathway combined with Cpd21 treatment did not produce detectable additive or synergistic effects (Fig. 7F). In fact, sMPNST cellular growth...
seemed relatively resistant to rapamycin, despite exhibiting decreased pS6 levels after rapamycin treatment (Fig. 7G). None of the other tested reagents produced measurable additive or synergistic effects (data not shown). We extended the above studies of dual LY294002 and Cpd21 treatment to MPNST cells derived from cis-Nf1<sup>+/−</sup>-p53<sup>+/−</sup> mice, and again, the combined effect of both inhibitors is greater than that of each individual inhibitor (Fig. 7H). We tested the effects of both inhibitors on phosphorylation of AKT and found that pAKT was inhibited only when LY294002 is present (Fig. 7C and I). Thus, in contrast to published reports of successful application of MEK inhibitors to suppress NF1-based solid tumors and leukemias, in the context of Cpd21, coinhibition of the PI3K pathway was most effective in impeding tumor cell growth and survival.

Discussion
Malignant peripheral nerve tumors are the major source of mortality in NF1. Like most malignant sarcomas, these tumors are resistant to all current chemotherapeutic and radiotherapeutic strategies. It has long been recognized that MPNSTs harbor tumor suppressor mutations in addition to Nf1 loss. Notably, loss-of-function mutations of the p53 tumor suppressor have been reported (16–18). This has led to the successful generation of spontaneous mouse models of MPNST by mutation of both Nf1 and p53 tumor suppressor genes (24, 25). A further refinement of MPNST modeling came about by identifying SKPs as a source for dermal neurofibromas and by the capacity of SKPs to engender plexiform neurofibromas when placed in the sciatic nerve (4). Additive mutation of p53 together with Nf1 turned SKPs into progenitors of MPNST, thus facilitating high-throughput screens for chemical compounds that might inhibit early passage cell growth.

We identified Cpd21 as a small molecule with inhibitory properties on cultured mouse and human MPNST cells. It was a surprise that this compound originating from a 200,000 chemical compound library, had, without chemical modification, a repertoire of desirable <i>in vivo</i> properties, including low micromolar EC<sub>50</sub>, adequate stability, manageable toxicity, and adequate accumulation in solid tumor tissue. These serendipitous favorable properties allowed allograft analysis of
antitumor efficacy and demonstrated a significant reduction in tumor burden by this compound. Future efforts to assess the effectiveness of Cpd21 on human MPNST xenografts will provide additional insight into the potential for this compound as a therapeutic agent.

At present we cannot identify the specific mechanism whereby Cpd21 exerts its inhibitory action on MPNST cells. Compound exposure to tumor cells results in a cell-cycle delay manifested by depletion of certain cell-cycle–related molecules and eventually leading to cellular apoptosis. A similar course of events is seen when tumor-bearing mice are treated with compound. However, the precise molecular target and mechanistic mode of compound action remains a topic of investigation. Empirical chemical compound screens to identify cancer cell inhibitory compounds have been applied for several decades. A significant proportion of such empirically derived cancer cell inhibitory small molecules that have reached the clinic have turned out to mechanistically impinge on various aspects of cell division, including mitotic spindle machinery, cell-cycle machinery, and DNA replication and repair machinery. These cellular properties are not unique to cancer cells and are shared by many normally dividing cells in the body that are
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essential for organ health. Chemotherapeutic toxicity to normal cells represents a major impediment to effective cancer treatment. In this regard, our screen departs from traditional high-throughput screens in that we limited our cells assayed to early passage cells rather than to established cell lines. It is also noteworthy that the cellular specificity of Cpd21 renders it relatively innocuous to the normally dividing cells we tested (MEFs, Myc-Schwann Cells, and wild-type SKPs). This feature is consistent with the idea that the compound target(s) relates to the ‘cancer state’ of the MPNST cells rather than to more general properties of mitotically active cells. Although we currently do not know whether Cpd21 is also effective against the benign plexiform neurofibromas, it is entirely possible that these slowly dividing tumor cells may also be susceptible to Cpd21 activity if they share common pathways with MPNSTs that are potential target(s) of Cpd21.

Recent advances in MPNST research have pointed to additional potential therapeutic targets, including the CXCR4 cytokine axis (7), the mTOR pathways (44), and the RAS/MEK/ERK pathways (13, 47), the mTOR pathways (44), and the RAS/MEK/ERK pathways (13, 47), the mTOR pathways (44), and the RAS/MEK/ERK pathways (13, 47), the mTOR pathways (44), and the RAS/MEK/ERK pathways (13, 47), the mTOR pathways (44), and the RAS/MEK/ERK pathways (13, 47), the mTOR pathways (44), and the RAS/MEK/ERK pathways (13, 47), the mTOR pathways (44), and the RAS/MEK/ERK pathways (13, 47), the mTOR pathways (44), and the RAS/MEK/ERK pathways (13, 47). In these studies, AMD3100 and rapamycin have been shown to inhibit MPNSTs from the cis-NF1/−/−; p53−/− mouse model, and ERK inhibitors, such as U0126, have been verified in a variety of human and mouse derived MPNSTs. Interestingly, when such compounds were tested in conjunction with Cpd21, we found no additive value. Instead, blockade of the PI3K pathway did cooperate with Cpd21 action to inhibit tumor growth. This intriguing result points to the potential plasticity of cancer cells and to the complexity of tumor pathway interactions. For example, it may be that Cpd21 activity somehow unveils a synthetic dependence on PI3K signaling that is not present in the absence of compound. Continued studies of Cpd21, its specific mode of action, and the mechanistic basis for its activity on MPNST cells but not on nontumorigenic cells may shed light on novel anticancer pathways.

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Disclosure of Potential Conflicts of Interest

V. Chau has ownership interest in patent pending for Cpd21. No potential conflicts of interest were disclosed by the other authors.

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