NVP-AUY922: A Novel Heat Shock Protein 90 Inhibitor Active against Xenograft Tumor Growth, Angiogenesis, and Metastasis


Abstract

We describe the biological properties of NVP-AUY922, a novel resorcylic isoxazole amide heat shock protein 90 (HSP90) inhibitor. NVP-AUY922 potently inhibits HSP90 (Kd = 1.7 nmol/L) and proliferation of human tumor cells with GI50 values of approximately 2 to 40 nmol/L, inducing G1–G2 arrest and apoptosis. Activity is independent of NQO1/DT-diaphorase, maintained in drug-resistant cells and under hypoxic conditions. The molecular signature of HSP90 inhibition, comprising induced HSP72 and depleted client proteins, was readily demonstrable. NVP-AUY922 was glucoronidated less than previously described isoxazoles, yielding higher drug levels in human cancer cells and xenografts. Daily dosing of NVP-AUY922 (50 mg/kg i.p. or i.v.) to athymic mice generated peak tumor levels at least 100-fold above cellular GI50. This produced statistically significant growth inhibition and/or regressions in human tumor xenografts with diverse oncogenic profiles: BT474 breast tumor treated/control, 21%; A2780 ovarian, 11%; U87MG glioblastoma, 7%; PC3 prostate, 37%; and WM266.4 melanoma, 31%. Therapeutic effects were concordant with changes in pharmacodynamic markers, including induction of HSP72 and depletion of ERBB2, CRAF, cyclin-dependent kinase 4, phospho-AKT/total AKT, and hypoxia-inducible factor-1α, determined by Western blot, electrochemiluminescent immunooassay, or immunohistochemistry. NVP-AUY922 also significantly inhibited tumor cell chemotaxis/invasion in vitro, WM266.4 melanoma lung metastases, and lymphatic metastases from orthotopically implanted PC3L3 prostate carcinoma. NVP-AUY922 inhibited proliferation, chemomigration, and tubular differentiation of human endothelial cells and antiangiogenic activity was reflected in reduced microvessel density in tumor xenografts. Collectively, the data show that NVP-AUY922 is a potent, novel inhibitor of HSP90, acting via several processes (cytostasis, apoptosis, invasion, and angiogenesis) to inhibit tumor growth and metastasis. NVP-AUY922 has entered phase I clinical trials. [Cancer Res 2008;68(8):2850–60]

Introduction

The molecular chaperone heat shock protein 90 (HSP90) is an exciting target in oncology (1–3). It supports the correct conformation, stabilization, activation, and localization of “client” proteins, many of which are involved in tumor progression (4). Targeting several pathways is essential to prevent tumor cell “escape” and development of drug resistance (3). The therapeutic efficacy of HSP90 inhibitors probably relates to the combinatorial blockade of multiple signaling pathways (3, 5, 6) and the increased levels of active HSP90 in tumors (7, 8), in some cases linked to clinical outcome (9). Tumors may also become addicted to pathways dependent on activated, mutated, or overexpressed client proteins, the mutated forms of which (e.g., BRAF) are often hypersensitive to HSP90 inhibitors (10, 11). Thus, for a variety of reasons, inhibition of HSP90 has considerable clinical potential.

The geldanamycin class of HSP90 inhibitors has been extensively evaluated. Geldanamycin analogues, specifically 17-allylamino-17-demethoxygeldanamycin (17-AAG; tansespimycin), 17-(dimethylaminoethyl-amino)-17-demethoxygeldanamycin (17-DMAG; alvespimycin), and the 17-AAG hydroquinone IPI-504, have been developed as less toxic and/or more soluble drugs (12, 13). 17-AAG and 17-DMAG have been in several phase I and II clinical trials where some disease stabilization and tumor responses were seen (14–16). However, this compound series has limitations, including formulation difficulties, hepatotoxicity, variable pharmacokinetics, and polymorphic metabolism by CYP3A4 (17) and NQO1/DT-diaphorase enzymes (18), together with efflux by P-glycoprotein (18). Nevertheless, these agents have been invaluable for showing proof of principle of therapeutic benefit preclinically and clinically, for establishing and validating robust biomarkers of target modulation (14, 19, 20), and for identifying additional activities, including inhibition of tumor invasion (21, 22) and angiogenesis (23, 24).

Other natural product HSP90 inhibitors include the macrolide radicicol and its derivatives (25). Radicicol is poorly soluble and inactive in vivo, although semisynthetic oxime derivatives have improved pharmacokinetics and exhibit antitumor activity (25).
However, these have not entered clinical development, possibly due to reported ocular toxicity (26).

There has been considerable effort to design synthetic small-molecule inhibitors based on the X-ray crystal structure of HSP90. Purine scaffold derivatives (e.g., PU3) showed parenteral activity in human tumor xenografts and soluble analogues exhibited oral antitumor activity at relatively high doses (27, 28). An oral purine scaffold compound (BIIBO21) is in clinical trial (29).

A second class of synthetic HSP90 inhibitors is the pyrazole resorcinols (Fig. 1A), initially exemplified by CCT018159 (30–32). Subsequent structure-based design generated more potent resorcylic pyrazole/isoxazole amide analogues (33, 34) and the significantly improved isoxazole resorcinol NVP-AUY922 (VER-52296). NVP-AUY922 is the most potent synthetic small-molecule HSP90 inhibitor yet described (35). We now report on the detailed in vitro activity and in vivo pharmacokinetic, pharmacodynamic, and efficacy profiles of NVP-AUY922 in a wide spectrum of human tumor cell lines and xenografts with different molecular pathologies and including orthotopic and metastatic models. These results support the selection of NVP-AUY922 for clinical development.

Materials and Methods

NVP-AUY922 synthesis, activity, and selectivity. NVP-AUY922 was synthesized as described (35). Its activity was assayed against HSP90α, HSP90β, GRP94, TRAP-1, HSP72, and topoisomerase II (31, 34). Profiling against a panel of kinases was carried out and screening against a panel of additional enzymes and receptors was performed at Cerep. X-ray crystallography, fluorescence polarization, and isothermal calorimetry were as described (35–37).

Cell proliferation and cell cycle progression. Unless otherwise stated, cell lines were from the American Type Culture Collection and grown in DMEM/10% FCS, 2 mmol/L glutamine, and nonessential amino acids in a humidified atmosphere of 5% CO₂ in air as described (Supplementary

Figure 1. Chemical structures of resorcinolic isoxazole/pyrazole HSP90 inhibitors and X-ray cocrystal structures. A, chemical structures of the 3,4 diarylpyrazole/isoxazole resorcinol HSP90 inhibitors. B, PyMOL cartoon showing NVP-AUY922 bound to the NH₂-terminal domain of HSP90α. C, PyMOL diagram showing binding interactions of NVP-AUY922. Dotted blue lines, hydrogen bonds; green, amino acid residues involved; cyan-colored spheres, water molecules; cyan, residues solely in van der Waals contact. D, two orthogonal views of the superimposition of VER-49009 (cyan), VER-50589 (magenta), and NVP-AUY922 (yellow) showing that NVP-AUY922, VER-49009, and VER-50589 bind with overall similarity. The structures for NVP-AUY922, VER-50589, and VER-49009 were obtained at 2.0 Å, 2.0 Å, and 2.1 Å resolution, respectively. For atomic coordinates and structure factors, see PDB codes 2CVI, 2UWD, and 2BSM, respectively.
information; refs. 23, 31, 34). All lines were free of Mycoplasma (Venor GeM kit, Minerva Biolabs). Cell proliferation was determined using the sulforhodamine B (SRB) assay (18) for tumor cells and prostate epithelial cells, the WST-1 assay (Roche Diagnostics Ltd.) for MCF10A and HB119, or an alkaline phosphatase assay (23) for HUVEC and HDMEC. GI50 was the compound concentration inhibiting cell proliferation by 50% compared with vehicle controls. Cell cycle analysis was as described (31). Activity caspase-3/7 was measured using a homogenous caspase assay kit (Promega).

Molecular biomarkers and tumor cell and endothelial cell activities. Effects of NVP-AUY922 on the expression of client proteins [e.g., CRAF, BRAF, cyclin-dependent kinase 4 (CDK4), ERBB2, AKT, and vascular endothelial growth factor receptor 2 (VEGFR2)] and on induction of HSP72 were determined in human tumor and endothelial cells (31, 34). Tumor cell chemotaxis, haptotaxis, invasion, and endothelial cell functions related to angiogenesis were also determined as described (23) with minor variations (see figure legends).

Measurement of NVP-AUY922 in biological samples. Micromolar incubations were performed with mouse and human liver preparations and human carcinoma cell uptake studies were as described (34). Given the relatively low GI50 for NVP-AUY922 in HCT116 colon carcinoma cells, we used 5 × GI50 for cell uptake studies and equimolar concentrations in HT29 cells.

Xenograft pharmacokinetic and efficacy studies. In vivo pharmacokinetic studies in female NCr athymic mice bearing WM266.4 human melanoma xenografts were essentially as described (34). NVP-AUY922 was dissolved in DMSO and diluted in sterile saline/Tween 20. A single dose of 50 mg/kg NVP-AUY922 was given i.v. or i.p. and groups of three animals were taken at intervals for pharmacokinetic analyses. Further details are in Supplementary information.

For efficacy studies, human tumor xenografts were established s.e. in athymic mice, WM266.4 cells were also injected i.v. to generate experimental lung metastases and PC3LN3 prostate carcinoma cells were implanted into the prostates of male mice. Dosing with NVP-AUY922 commenced when tumors were well established using schedules described. Tumor growth was monitored and at study end samples were harvested for analysis. Further details are provided in Supplementary information.

Biomarker analyses by Western blotting, immunoassay, and immunohistochemistry. Snap-frozen tumors were lysed, protein concentration was determined, and standard Western blotting procedures were followed (34). The levels of phospho-AKT and/or total AKT, HSP72, ERBB2, phospho-AKT, HSP72, ERBB2, phospho-ERBB1 (ERK1/2), and hypoxia-inducible factor-1 (HIF-1a) in treated and control tumor xenografts were determined by electrochemiluminescent immunoassay (Meso Scale Discovery). Cryopreserved tumors were sectioned and stained for phosphoproteins. Details are in Supplementary information. Tumor microvessel density was determined as described (23).

Results

NVP-AUY922 binds to the NH2-terminal nucleotide site in HSP90. The X-ray co-crystal structure of NVP-AUY922 (Fig. 1A) bound to the NH2-terminal domain of recombinant human HSP90a is shown in Fig. 1B and C. This confirms the crucial network of hydrogen bonding interactions including the resorcinol residue and heterogeneous ring with Asp353, Thr183, and a cluster of structurally conserved and highly ordered water molecules, as for CCT018159, VER-49009, and VER-50589 (31, 33, 34). In addition, as observed with VER-49009 and VER-50589, the C-5 ethylamide residue of NVP-AUY922 provides additional hydrogen bonding interactions with the protein backbone via Lys38 and Gly55, the latter being particularly important (33). Replacement of the chlorine of the resorcinol ring in VER-49009 or VER-50589 by an isopropyl group in NVP-AUY922 results in an additional hydrophobic interaction with Leu297 in the flexible lipophilic pocket (Fig. 1C). Further hydrophobic interactions are also seen with Thr109 and Gly135 when the methoxy group of VER-49009 or VER-50589 is replaced with the morpholino moiety of NVP-AUY922. The morpholine ring is located close to the surface of the protein (Fig. 1B). The two orthogonal views of the superimposition of VER-49009, VER-50589, and NVP-AUY922 show that all three compounds bind with overall similarity (Fig. 1D).

NVP-AUY922 is a potent and selective HSP90 inhibitor. The competitive binding fluorescence polarization assay gave an IC50 for NVP-AUY922 of 21 ± 16 nmol/L against HSP90β (35) and of 7.8 ± 1.8 nmol/L for HSP90α. Inhibitory kinetics were competitive and the Ki values were 9.0 ± 5.0 nmol/L and 8.2 ± 0.7 nmol/L for HSP90α and HSP90β respectively (mean ± SE, n = 3). Isothermal calorimetry showed a very high binding affinity to HSP90β with a KD of 1.7 ± 0.5 nmol/L, 3-fold lower than VER-50589 (35.8). The enthalpy of binding of NVP-AUY922 is ~12.24 kcal/mol, ~3 kcal/mol more favorable than for VER-50589 (34). The entropy of binding of NVP-AUY922 is almost negligible (0.19 cal/mol/K), indicating that the binding event is driven essentially exclusively by enthalpy (i.e., bonding interactions). NVP-AUY922 exhibits the tightest binding of any small-molecule HSP90 ligand yet reported.

The IC50 values for NVP-AUY922 against the HSP90 family members GRP94 and TRAP-1 were 535 ± 51 nmol/L (Ki = 108 nmol/L) and 85 ± 8 nmol/L (Ki = 53 nmol/L), respectively, indicating weaker potency than for HSP90. The fluorescence polarization IC50 for binding to HSP90 in human cell lysates was in the range of 6.0 ± 1.8 to 13.7 ± 1.4 with no clear differences between tumor cells (HCT116 and WM266.4) and nontumorigenic cells (HUVEC and PNT2 prostate epithelial cells). NVP-AUY922 at 10 μmol/L showed no inhibition of human HSP72 ATPase or the decatenation activity of human topoisomerase II and little or no activity against a range of 13 kinases (Supplementary Table S1). In a screen of 14 additional enzymes and 67 receptors, NVP-AUY922 exhibited >50% inhibitory activity at 10 μmol/L against only 6 receptors and 1 enzyme; further profiling showed NVP-AUY922 to be >50-fold selective for HSP90 (data not shown).

NVP-AUY922 potently inhibits proliferation of multiple human tumor cell lines in vitro. NVP-AUY922 inhibited with nanomolar potency (2.3–496 nmol/L) the in vitro proliferation of human tumor cells selected for their different tissue origins and molecular features (Supplementary Table S2). Unlike the geldanamycin-based HSP90 inhibitor 17-AAG (18, 38), NVP-AUY922 activity is independent of NQO1/DT-diaphorase activity because sensitivity was similar in BENeG human colon carcinoma cells carrying an inactivating NQO1 polymorphism and isogenic BE2 cells transfected with the NQO1 gene and also in SKMEL2 (high NQO1) and SKMEL5 (low NQO1) melanoma cells. Activity was maintained in doxorubicin-resistant CH1 ovarian carcinoma cells overexpressing P-glycoprotein and in oxaliplatin-resistant HT29 colon carcinoma cells. In addition, unlike some cytotoxic agents and radiotherapy, NVP-AUY922 was equally effective under hypoxic conditions. In PC3 and DU145 prostate carcinoma cells exposed to NVP-AUY922 in 20% or 1% O2, the ratios of GI50 values were 1.17 and 1.20, respectively, whereas for paclitaxel the GI50 values were increased by 3.8- and 5.6-fold under hypoxia (data not shown). Nontumorigenic human prostate (PNT2 and Pre2.8) and breast (MCF10A and HB119) epithelial cells, at least when actively proliferating, showed similar sensitivity to NVP-AUY922 as tumor cells, as also seen with 17-AAG. Human endothelial cells (HUVEC and HDMEC) were among the most sensitive (Supplementary Table S2).

NVP-AUY922 induced marked accumulation in either G1 or G2 plus G2-M phases in most cell lines. More detailed analysis using continuous bromodeoxyuridine (BrdUrd) labeling and
bivariate Hoechst-propidium iodide flow cytometry showed that NVP-AUY922 arrested HCT116 colon carcinoma cells in the original G₁ and G₂-M as early as 8 h (Fig. 2A). By 16 h, cells in S phase that had traversed to the new G₂* phase remained blocked over 72 h. The ability of NVP-AUY922 to induce apoptosis was cell line dependent. Activated caspase-3/7 levels rapidly increased in BT474 cells following exposure to NVP-AUY922 and apoptosis was confirmed by Western blotting for cleaved poly(ADP-ribose) polymerase (data not shown). In WM266.4 melanoma cells, activated caspase-3/7 increased moderately, whereas in MDA-MB-231 breast carcinoma and HCT116 colon carcinoma cells no increase was observed (Fig. 2B). Further analysis revealed that cell death could occur independently of caspase activation. Following 72-h exposure to 6 to 8 × GI₅₀ concentrations of NVP-AUY922, the fraction of either BT474 or MDA-MB-231 breast carcinoma cells remaining was approximately 15% to 18% of pretreatment levels (Fig. 2C). In contrast, exposure of HCT116 colon carcinoma cells to 8 × GI₅₀ NVP-AUY922 resulted in virtually no cell death, suggesting a predominantly cytostatic effect in this cell line.

These observations were confirmed by colony formation assays. The concentration of NVP-AUY922 required to reduce colony numbers to <1% following 24-h exposure was ~32 nmol/L for MDA-MB-231 cells but 250 nmol/L in HCT116 cells. This is not due to lack of client protein depletion as exposure of HCT116 cells to 5 × GI₅₀ NVP-AUY922 led to a rapid depletion of CRAF and ERBB2 and concomitant induction of HSP72 (Fig. 2D). Despite being extremely sensitive to growth inhibition by NVP-AUY922, SKBR3 breast carcinoma cells also underwent cytostasis following exposure to NVP-AUY922 or 17-AAG (data not shown).

NVP-AUY922 shows high uptake in HCT116 human colon carcinoma cell lines in vitro. HT29 colon carcinoma cells express uridine diphosphoglucuronosyltransferases, whereas HCT116 cells do not (31, 39). At equimolar concentrations, initially high uptake was seen in both cell lines; however, ~3-fold more NVP-AUY922 was detected in HCT116 colon carcinoma cells following 1-h exposure (547.7 ± 4.5 pmol/10 million cells in HCT116 versus 172.0 ± 10.0 in HT29). Levels increased from 1 to 24 h to 687.0 ± 1.7 pmol/10 million cells in HCT116 cells but were hardly detectable at 24 h in HT29 cells (4.2 ± 0.8 pmol/10 million cells). This suggests that glucuronidation of NVP-AUY922 during this period results in the reduced sensitivity in HT29 cells compared with HCT116 cells.

NVP-AUY922 depletes HSP90 client proteins in a concentration- and time-dependent manner. The molecular signature of HSP90 inhibition comprises induction of HSP72 coupled with depletion of client proteins in a concentration- and time-dependent manner (14, 19). Biomarker changes were observed in HCT116 colon carcinoma cells (Fig. 2D) and in A2780 ovarian, SKMEL2 and WM266.4 melanoma, and BT474 breast carcinoma cells (Supplementary Fig. S1A-D). HSP72 levels were increased from 8 to 72 h. ERBB2 was almost completely depleted in all cell lines for the duration of the study. BRAF (both wild-type and

Figure 2. NVP-AUY922 induces cell cycle arrest and apoptosis and depletes client proteins in human cancer cells in vitro. A, representative cell cycle profiles of mutant KRAS HCT116 human colon carcinoma cells treated with vehicle (left) or 80 nmol/L (5 × GI₅₀) concentration of NVP-AUY922 (right) for 0, 8, 16, 24, and 72 h determined using continuous BrdUrd labeling and bivariate Hoechst-propidium iodide flow cytometry. B, BT474 breast carcinoma (circles), WM266.4 melanoma (triangles), MDA-MB-231 breast carcinoma (diamonds), or HCT116 colon carcinoma cells (squares) were exposed to increasing concentrations of NVP-AUY922 for 24 h. The amount of active caspase-3/7 was determined using a homogenous caspase assay kit. C, SRB determination of cell survival following exposure to NVP-AUY922 of BT474 (16 nmol/L), HCT116 (125 nmol/L), or MDA-MB-231 (40 nmol/L) cells for 72 h. Cell survival was determined as the percentage of cell mass remaining compared with that present at the start of NVP-AUY922 dosing. D, Western blot of HCT116 cells treated with 80 nmol/L (5 × GI₅₀) NVP-AUY922 and analyzed over 72 h. GAPDH, glyceraldehyde-3-phosphate dehydrogenase.
Plasma pharmacokinetic variables compared well with those described for other pyrazole and isoxazole HSP90 inhibitors (31, 34), with similar fast clearances following both i.p. and i.v. administration to athymic mice bearing WM266.4 human melanomas (Fig. 4A–D). However, as predicted from its decreased metabolism and high cellular uptake, NVP-AUY922 showed enhanced tissue distribution with ratios of ≥4.0 in WM266.4 tumors, liver, and spleen compared with plasma following i.v. administration. Importantly, tumor clearance was significantly lower than that of normal tissues, with a longer terminal half-life of 14.7 to 15.5 h. This resulted in tumor NVP-AUY922 levels at least 100 × GI50 concentrations over 24 h following both i.v. and i.p. administration. Similar pharmacokinetic profiles were observed in other human tumor xenografts as indicated below.

NVP-AUY922 inhibits HSP90 and exhibits potent antitumor efficacy in human tumor xenografts. Following five daily i.p. doses of 50 mg/kg NVP-AUY922 to athymic mice bearing BRAF mutant WM266.4 melanoma xenografts, liquid chromatography-tandem mass spectrometry analysis indicated NVP-AUY922 concentrations of 6.8 to 7.7 μmol/L in tumors over 24 h (Supplementary Table S3). As quantified by electrochemiluminescent immunoassay, ERBB2 levels were reduced to a nadir of 7.3% of controls at 6 h, remaining below 35% over 24 h. Phospho-ERK1/2 levels were 65% to 83%, phospho-AKT levels were 13% to 51%, AKT levels were 57% to 65%, and HIF-1α levels were 60% to 85%. HSP72 expression was increased to 247% to 281% of controls over the 24-h period.

The therapeutic effect of NVP-AUY922 was determined against established WM266.4 melanoma xenografts. Daily doses of 75 mg/kg caused ∼10% body weight loss; thus, doses were reduced to 50 mg/kg/d after eight doses and body weights rapidly recovered. NVP-AUY922 significantly inhibited tumor growth rate, reducing the mean weights of tumors on day 11 from 252 ± 19 mg in controls to 78 ± 6 mg (Fig. 5A). Tumor samples on day 11 (24 h after the final dose) showed the HSP90 inhibition signature of depleted ERBB2 and CDK4, with induced HSP72 (Fig. 5B).

We next tested 50 mg/kg NVP-AUY922 given i.p. or i.v. daily against established WM266.4 melanoma xenografts. The treatment regimens were well tolerated with either no (i.p.) or <5% (i.v.) differences in mean body weights compared with controls. Tumor weights after 9 days of treatment were reduced by 55% in the i.v. group (P = 0.000085) and by 46% in the i.p. group (P = 0.00067) compared with controls. Biomarker changes confirmed HSP90 inhibition in tumor as in the previous study. Both routes of administration gave comparable levels of NVP-AUY922 in the tumors (similar to those reported above in the single dose studies), consistent with the comparable efficacy and pharmacodynamic changes observed. In three additional studies, mice with established WM266.4 tumors were treated with different schedules of NVP-AUY922, and in all cases, significant growth delays were observed, with some recovery of growth rate toward the end of dosing (Supplementary Table S5).

We also tested the ability of NVP-AUY922 to inhibit established disseminated melanoma. Therapy commenced 7 days after i.v. injection of WM266.4 melanoma cells and continued for 32 days (50 mg/kg five times weekly for 18 days, three times weekly for a further 14 days). Histologic examination of lungs indicated that both the number and size of lung metastases were decreased by NVP-AUY922 treatment (Fig. 5C). The mean number of metastases was reduced from 61 ± 13 to 17 ± 3 (72% inhibition; P = 0.0037) and the total area occupied by the metastases decreased from...
2.38 ± 0.43 mm² to 0.15 ± 0.04 mm² (93.7% inhibition; \( P = 0.0003 \)) as shown in Fig. 5.

We then determined the efficacy of NVP-AUY922 in established PTEN-null U87MG human glioblastoma xenografts. Again, highly significant growth inhibition was obtained; indeed, regressions were observed because mean tumor volumes on day 18 were decreased to 58% of day 0 values (Fig. 6A). HSP90 inhibition was confirmed by Western blot with significant depletion of ERBB2, AKT, phospho-ERK1/2, HIF-1α, and survivin together with increased HSP72 (data not shown). We also showed clear depletion of phospho-AKT (Ser473) and phospho-S6 (Ser240/244) in histologic sections, consistent with inhibition of the phosphatidylinositol 3-kinase (PI3K) pathway (Fig. 6B). Figure 6C shows that levels of HIF-1α and AKT were decreased to 39% and 27% of controls, respectively, and HSP72 levels increased by f800% as measured by electrochemiluminescent immunoassay. Finally, microvessel density was significantly reduced in NVP-AUY922–treated tumors, suggesting an antiangiogenic effect (Fig. 6D).

A parallel pharmacokinetic/pharmacodynamic study of five daily doses (50 mg/kg i.p., comparable with that described above for WM266.4) was performed in U87MG xenografts. Mean tumor NVP-AUY922 concentrations were 3.8 to 6.7 μmol/L from 6 to 24 h following the last dose (Supplementary Table S4). Phospho-AKT expression was reduced to 19% to 56%, AKT to 74% to 80%, and HIF-1α to 32% to 48% of controls over 6 to 24 h. Phospho-ERK1/2 levels were apparently not decreased in this tumor but HSP72 expression was increased to 228% to 530% of controls (data not shown).

The therapeutic efficacy of NVP-AUY922 was explored in further human tumor xenografts of varying histogenic origins and with differing molecular abnormalities. Strong inhibitory effects were obtained in the PTEN and PIK3CA mutant A2780 ovarian carcinoma [treated/control (T/C) of 10.5% after 8 daily treatments with 50 mg/kg i.p.; Supplementary Fig. S5A] and the ERBB2+ ERα+ BT474 breast carcinoma (T/C of 21% after 24 daily treatments; Supplementary Fig. S5B). In the latter case, regressions were observed in 5 of 12 tumors. Body weight loss was <5% and clear biomarker changes consistent with HSP90 inhibition were obtained in both studies (Supplementary Fig. S5C and D). In BT474, complete loss of ERBB2 and substantial depletion of ERα were shown, in addition to reductions in CDK4 and phospho-ERK1/2.

Finally, we explored the ability of NVP-AUY922 (50 mg/kg daily i.p.) to inhibit growth and spontaneous metastasis in an established orthotopic and metastatic PTEN-null human prostate...
carcinoma xenograft model (PC3LN3). Primary tumor growth was reduced (Supplementary Fig. S6A), as was the incidence and mass of local lymph node metastases (Supplementary Fig. S6B). Fifty-three percent of control animals developed distant lymph node metastases, but none was detected in the NVP-AUY922–treated animals. Western blots showed induction of HSP72, strong depletion of ERBB2, and weak but detectable depletion of CDK4 (Supplementary Fig. S6C). The antitumor activity of NVP-AUY922 in all human tumor xenograft models tested is summarized in Supplementary Table S5.

Discussion

NVP-AUY922 was discovered in a multiparameter lead optimization program (33) based on a high-throughput screening hit (30). Initial activities focused on improving potency against the HSP90 target using X-ray crystallography and structure-based drug design, resulting in the resorcinol pyrazole amide VER-49009 (31, 33). Replacement of the pyrazole with isoxazole led to VER-50589 with further increments in target affinity and enhanced cellular uptake and antiproliferative activity with acceptable pharmacokinetic-pharmacodynamic properties, leading to antitumor activity in HCT116 xenografts (34). Further lead optimization, focussing on maintaining or increasing potency while improving physicochemical properties and pharmacokinetic-pharmacodynamic behavior, resulted in NVP-AUY922 (35).

To our knowledge, NVP-AUY922 exhibits the highest affinity of any synthetic small-molecule inhibitor yet reported for the NH2-terminal nucleotide-binding site of human HSP90, with a $K_d$ of $1.7 \pm 0.5 \text{nmol/L}$. The binding potency is explained by the bonding...
interactions revealed by the X-ray cocrystal structure, together with the entropy and enthalpy factors. NVP-AUY922 also exhibited a degree of selectivity against the HSP90 target over the highly homologous HSP90 family members GRP94 and TRAP-1. This is distinct from 17-AAG, which exhibits moderate selectivity over GRP94 but is highly selective against TRAP-1. In addition, NVP-AUY922 at 10 μmol/L showed no significant inhibition of the related GHKL family member human topoisomerase II, was inactive against human HSP72, and exhibited little or no inhibition of a large panel of additional kinases, other enzymes, and receptors.

The human tumor cells sensitive to NVP-AUY922 represent diverse tissue origins and were selected to exhibit a range of key molecular abnormalities, including PTEN loss (e.g., PC3 and U87MG) and expression of activated oncogenes such as the ERBB family (e.g., BT474, SKBR3, T47D, and DU145), mutant KRASt (HCT116), mutant PIGKCA (HCT116, A2780, and BT474), mutant BRAF (WM266.4, SKMEL28, BE, and HT29), and mutant TP53 (SKMEL2 and SKMEL28). The activity seen across the tumor cell line panel (Supplementary Table S2) suggests that NVP-AUY922 could have wide therapeutic applicability. Its cellular potency is significantly enhanced compared with earlier isoxazole and pyrazole resorcinols developed in this research program. Mean GI50 values in comparable tumor cell panels are as follows: NVP-AUY922, 10.8 nmol/L versus 5,300 nmol/L for CCT018159, 685 nmol/L for VER-49009, and 78 nmol/L for VER-50589, representing a \(5,000\)-fold improvement from the original hit and a 6.6-fold enhancement compared with the recently reported isoxazole VER-50589 (34). Importantly, NVP-AUY922 activity is independent of NQO1/DT-diaphorase metabolism, is equally effective in cells with acquired resistance to oxaliplatin or doxorubicin, and retains activity under hypoxic conditions.

In human HCT116 colon carcinoma cells and others, exposure to NVP-AUY922 resulted in G1 and G2-M arrest. However, this is cell line and tumor type dependent, as seen with other HSP90 inhibitors (31, 40), because G1 arrest only was observed in SKMEL5 melanoma cells and BT474 breast cancer cells. There was clear evidence of concentration- and time-dependent biomarker modulation and induction of HSP72 expression, the accepted molecular signature of HSP90 inhibition (14, 19). At 5 × GI50 concentrations, client protein depletion was usually evident by 8 h, although CDK4 levels fell later and recovered sooner or in some cells were relatively unaffected. Inhibition of signaling (as evidenced by the loss of...
phosphorylated ERBB2 and AKT in high ERBB2-expressing breast carcinoma cells) could often be detected before degradation of client protein. Previous reports have shown that depletion of key client proteins (such as ERBB2 and AKT) is closely correlated with antiproliferative effects of benzoquinone ansamycin HSP90 inhibitors and that the pharmacodynamic changes are generally seen at 4 to 5 × GI50 concentrations (14, 19). Our findings with NVP-AUY922, a member of a different chemical class of HSP90 inhibitor, are consistent with these observations.

Cell fate following HSP90 inhibition varied between cell lines and involved caspase-dependent or caspase-independent cell death or cytostasis. It is likely that the expression of factors downstream of loss of client protein signaling following HSP90 inhibition is critical for subsequent cell fate. Identification of factors that confer cell survival through induction of cell stasis rather than death may help to determine sensitive patient populations. The fact that inhibition of other cellular functions (such as chemomigration) occurs at concentrations below those required for cytostasis attests to their particular reliance on HSP90 chaperones (22).

In addition to the enhanced cellular potency of NVP-AUY922, further advantages were obtained from decreased microsomal metabolism, leading to reduced glucuronide metabolite in plasma compared with previously described pyrazoles and isoxazoles (32, 34). This translated into a significant improvement in tumor distribution. Indeed, NVP-AUY922 was selected from a set of similar compounds based on sustained high tumor levels following cassette dosing in tumor-bearing mice (35). Following i.v. and i.p. administration of 50 mg/kg NVP-AUY922, tumor levels were ~100 × GI50 and sustained for at least 24 h. Given the cellular accumulation observed with NVP-AUY922, it is likely that high concentrations are required in tumors for robust target inhibition and therapeutic efficacy. HSP90 is abundant in tumor cells. The concentration of 820 to 1,100 nmol NVP-AUY922/million cells measured in HCT116 following treatment with 5 × GI50 concentrations would correspond to ~5 μmol/L in tumor tissue based on protein measurements. These levels are within the concentration range observed following single and multiple dosing in animals (Fig. 4). Similar high levels were observed in human tumor xenograft models following 17-AAG treatment (19) and would be predicted to occur in cancers of treated patients based on plasma pharmacokinetics (14).

NVP-AUY922 was well tolerated in mice at 50 mg/kg/d and showed excellent target inhibition evidenced by depletion of multiple client proteins and induction of HSP72, leading to therapeutic efficacy in a wide variety of human tumor xenografts with different molecular pathologies. The results compare favorably with those for VER-50589 (34) and with other HSP90 inhibitors (29, 41). Significant

![Figure 6](image_url)

**Figure 6.** NVP-AUY922 shows therapeutic activity against established PTEN-null U87MG human glioblastoma xenografts. Tumors were established s.c. bilaterally in the flanks of female NCr athymic mice as described in Supplementary Materials and Methods. Groups of eight animals were randomized to vehicle or drug treatment when the mean tumor diameter was 5 to 6 mm (day 8 after tumor cell implantation). Animals received 50 mg/kg NVP-AUY922 i.p. five times weekly (or an equivalent volume of vehicle) for 18 d when the study was terminated and samples were obtained for analyses. Results are expressed as % of tumor volumes at the commencement of therapy. A, xenograft tumor growth curves, with final weights and other metrics (inset). ■, vehicle controls; ○, NVP-AUY922 treated. B, immunostaining for phospho-AKT and phospho-S6 in tumor xenografts. C, electrochemiluminescence immunoassay measuring tumor levels of HIF-1α, AKT, and HSP72. D, tumor microvessel density with representative images of vessel staining (inset above). Left, control; right, NVP-AUY922 treated. P < 0.0001, Student’s t test.
Characterization of Novel HSP90 Inhibitor NVP-AUY922

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