FLT-PET Is Superior to FDG-PET for Very Early Response Prediction in NPM-ALK-Positive Lymphoma Treated with Targeted Therapy

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Abstract

The prognosis of relapsed or refractory aggressive lymphoma is poor. The huge variety of currently evolving targeted treatment approaches would benefit from tools for early prediction of response or resistance. We used various ALK-positive anaplastic large cell lymphoma (ALCL) cell lines to evaluate two inhibitors, the HSP90 inhibitor NVP-AUY922, and the mTOR inhibitor everolimus, both of which have shown to interfere with ALK-dependent oncogenic signal transduction. Their therapeutic effect was determined in vitro by MTT assay, [18F]fluorodeoxyglucose (FDG)- and [18F]fluorothymidine (FLT)-uptake, and by biochemical analysis of ALK-induced signaling. Micro-FDG- and FLT-potision emission tomography (PET) imaging studies in immunodeficient mice bearing ALCL xenotransplants were carried out with the cell lines SUDHL-1 and Karpas299 to assess early treatment response to NVP-AUY922 or everolimus in vivo. SUDHL-1 cells showed sensitivity to both inhibitors in vitro. Importantly, we detected a significant reduction of FLT-uptake in SUDHL-1 bearing animals using both inhibitors compared with baseline as early as 5 days after initiation of targeted therapy. Immunostaining showed a decrease in Ki-67 and an increase in cleaved caspase-3 staining. In contrast, FDG-uptake did not significantly decrease at early time points. Karpas299 xenotransplants, which are resistant to NVP-AUY922 and sensitive to everolimus treatment, showed an increase of mean FLT-uptake on day 2 after administration of NVP-AUY299, but a significant reduction in FLT-uptake upon everolimus treatment. In conclusion, we show that FLT-PET but not FDG-PET is able to predict response to treatment with specific inhibitors very early in the course of treatment and thus enables early prediction of treatment efficacy. Cancer Res; 72(19); 5014–24. © 2012 AACR.

Introduction

The standard therapy for aggressive non-Hodgkin lymphoma (NHL) are cyclophosphamide-Adriamycin-vincristine-prednisone-like regimens, in the case of B-cell origin combined with rituximab (1). However, not all aggressive NHL patients show a favorable outcome. Relapsed or refractory disease is a substantial clinical problem with a poor prognosis. On the basis of molecular insights into different lymphoma subtypes, a large number of druggable molecules have been identified. These molecules include receptor signaling molecules (e.g., BTK, Syk, PKCβ), antiapoptotic proteins, deacetylases, and immune modulators (2, 3). Although these approaches are promising a substantial number of patients does not benefit from these targeted therapeutics. Given that various novel compounds will be available for the treatment of relapsed/refractory lymphoma in the future, the implication of predictive biomarkers will be critical. However, regression of lymphomas in the course of the therapy is a very important endpoint. Thus, evaluation of response early in the course of the therapy will help to optimize treatment modalities, avoid ineffective treatment, and reduce costs.

FDG-potisitron emission tomography (PET) imaging has been successfully used for imaging lymphoma with proven implications for prognosis after completion of therapy (4, 5). In addition, interim FDG-PET has been used to monitor response to therapy (6, 7). In these studies, interim PET was predictive for progression-free survival (PFS) and overall survival. However, in some studies the specificity and predictive value of interim PET was very limited (8, 9). In a study that included biopsies of PET-positive lesions, FDG-PET was not predictive of treatment response (10, 11).
for PFS (10). These limitations are based on the fact that FDG uptake is not tumor-specific and false-positive findings can be generated by inflammation (11). Tracers that are capable to distinguish lymphoma tissue from inflammatory tissue are required.

Deregulated cell cycle progression is a hallmark of cancer. With respect to in vivo imaging, proliferative activity has been shown to be more specific for malignant tumors than that of glucose metabolism (12). The thymidine analogue \(^{3}\text{-deoxy-3'-[\text{\textsuperscript{18}F]}}\)fluorothymidine (FLT) is a stable PET tracer that accumulates in proliferating tissues and malignant tumors (13). In line, the thymidine kinase 1 has been revealed as a key enzyme responsible for the intracellular trapping of FLT (14). Several studies in humans showed a significant correlation of tumor proliferation and FLT uptake (15–17). As a preclinical model for monitoring therapeutic response, a significant decrease of FLT uptake was observed in tumor-bearing mice as early as 24 hours after chemotherapy (18–20). We showed that the reduction of FLT uptake in aggressive lymphomas after the first course of therapy correlates with response at the end of the treatment (21).

A total of 50% to 60% of anaplastic large cell lymphoma (ALCL) are associated with the t(2;5)(p23;q35) chromosomal translocation involving the anaplastic lymphoma kinase (ALK) gene (22, 23). The t(2;5) results in the expression of the oncogenic fusion protein nucleophosmin-ALK (NPM-ALK). A number of studies have shown that the constitutively active tyrosine kinase function of NPM-ALK is a key oncogenic event in the pathogenesis of t(2;5)-positive ALCLs, which leads to the constitutive activation of several signaling pathways including the STAT3, PI-3K/Akt, and mTOR pathways (24, 25). Thus, ALK as well as ALK-dependent signaling events constitute therapeutic targets for the treatment of ALCL. Besides ALK inhibitors, which are now being tested in preclinical and clinical studies, heat shock protein 90 (HSP90) inhibition leading to ALK degradation as well as mTOR inhibition are highly effective approaches to ALK-positive ALCL cells in vitro (26, 27).

In this report, severe combined immunodeficient (SCID) mice bearing ALK-positive lymphoma xenotransplants were treated with the HSP90 inhibitor NVP-AUY922 (AY922) and the mTOR inhibitor everolimus. Micro-PET imaging using FDG and FLT as tracer was applied to predict response to targeted therapy very early in the course of treatment. Our studies contribute to the understanding of functional imaging in lymphoma exposed to pathway-specific drugs and provide the opportunity to individualized targeted treatment.

Materials and Methods

Cell lines and animals

The human t(2;5) ALCL cell lines SUDHL-1, Karpas299, and SR-786 were obtained from and propagated as suggested by the German Collection of Microorganisms and Cell Cultures (DSMZ) and were authenticated by DSMZ using DNA-typing and PCR analysis as well as cytogenetic testing. Cells used for all experiments were passaged for fewer than 6 months after receipt. JB-6 were obtained from S. Morris. Ba/F3 cells (originally obtained from DSMZ) transfected with NPM-ALK (Ba/F3-NA) were obtained from Justus Duyser. Cells were cultured in RPMI 1640 medium containing 10% FBS, 1mmol/L L-glutamine and 1% penicilline/streptomycin (Gibco). A total of 6- to 8-week-old female immunodeficient mice (CB-17 SCID) were obtained from Charles River Laboratories. For induction of tumors \(10 \times 10^6\) SUDHL-1 or \(5 \times 10^6\) Karpas299 cells suspended in sterile PBS (100 µL) were injected subcutaneously into the right shoulder region. All animal experiments were authorized by the regional government agency (Regierung von Oberbayern, Az. 55.2-1-54-2531-52-07).

Inhibitors

AY922 (HSP90 inhibitor) and everolimus (mTOR inhibitor) were provided by Novartis. AUY922 and everolimus were solubilized in 5% glucose to 200 µmol/L or 1 µmol/L stock solution and stored at –20°C. The primary solution was diluted to 0 to 1,000 nmol/L for AUY922 and 0 to 100 nmol/L for everolimus with RPMI 1640 medium for cell culture.

MTT assay

MTT assays were carried out according to the manufacturer’s instruction (Promega). Briefly, \(10^6\) SUDHL-1 or Karpas299 cells per well (96-well plate) were incubated at 37°C with different concentration of inhibitors for 48 hours. A total of 20 µL of MTT dilution in PBS was added per well and cells were incubated for 90 minutes. Absorbance was measured at 570 nm using a Bio-Tek ELx800 Series Universal Microplate Reader (Progen Scientific).

Flow cytometry

Lymphoma cells (5 \(\times\) 10^5/well in 12-well plates) were incubated with inhibitors at 37°C. After 48 hours cells were centrifuged (1,700 U/min, 7 min) and stored in 3 mL ethanol (70%) at –20°C. On the day of analysis, cells were centrifuged again and resuspended in 300 µL PBS. After RNA-digestion by ribonuclease A (95%; Sigma-Aldrich), propidium iodine (Sigma-Aldrich) was added in a 1:500 dilution. Cells were incubated for 30 minutes at 37°C and analyzed (Beckman Coulter). To assess apoptosis, 5 \(\times\) 10^5 cells were stained with fluorescein isothiocyanate-labeled Annexin V (BD Pharmingen) and counterstained with propidium iodide (PI; Sigma-Aldrich). Following incubation cells were washed, resuspended in PBS, and analyzed by flow cytometry (Beckman Coulter).

Immunoblotting

Cells were incubated with inhibitors at 37°C. After 48 hours cells were washed, pelleted, and stored at –80°C. Cells were lysed and the protein concentration was determined using protein assay dye reagent (Bio-Rad) with bovine serum albumin as standard. For immunoblotting, 50 µg protein per lane was separated on a 7.5% gradient readymade SDS-6Gel (BioRad) and transferred to a polyvinylidene difluoride (Millipor Corporation) membrane. Primary antibodies (ALK or p-Tyrosine-ALK, AKT or p-AKT, STAT3 or p-STAT3, p70S6K or p-p70S6K, all from Cell Signaling) were incubated for 90 minutes. Absorbance was measured at 405 nm using a Multiwell Reader (Progen Scientific). Blots were developed using Pierce ECL Western blotting reagent.
Fast Western Blot Kit and exposed to film (Fisher Thermo Scientific).

**FLT- and FDG-uptake in vitro**
Lymphoma cells (5 × 10^7/well in 12-well plates) were incubated with different concentrations of inhibitors at 37°C for 48 hours. After cell counting, 100 μL of tracer solution was added and incubated (45 minutes, 37°C). Tracer solution consisted of 0.9% sodium chloride and FLT or FDG with an activity of 370 kBq. Cells were washed 3 times with PBS before measuring activity in counts per minute (cpm) using an automated gamma-counter (Cobra II, Packard Instrument). Results of cells were adjusted to 10^6 cells per well. The cellular uptake of tracer was calculated using the formula [original cpm of cells/standard value (cpm)]^* 100%.

**Tumor volume and therapeutic regimens**
Tumor diameters were measured daily with a shifting caliper and tumor volume was calculated using the formula \( \text{tumor volume} = \text{length} \times \text{width}^2 / 2 \). Treatment was carried out when the xenotransplants reached a size of approximately 500 mm³. Lymphoma bearing animals were treated daily with AUY922 (25 mg/kg i.p.), everolimus (5 mg/kg orally), or carrier (glucose D-glucose were synthesized as previously described (28; Radiopharmacy Unit, TU München). Imaging was conducted using a micro-PET system (Inveon, SIEMENS Preclinical Solutions), FLT or FDG was administered via tail vein injection (100 μL) at an activity dose of 5 to 10 MBq per mouse. The accumulation of radiotracer in the tumor was allowed for 60 minutes. Mice were then imaged for a 15 minutes static acquisition.

**PET data analysis**
Tumor-to-background ratios (TBR) were calculated to semi-quantitatively assess the tracer accumulation in the tumor. Circular three-dimensional regions of interest (ROI) were placed manually in the area with the highest tumor activity. The diameter was not covering the entire tumor volume to avoid partial volume effects. For determination of background activity, 2 three-dimensional ROIs were placed in the spinal muscle at the level of the kidneys. Corresponding TBR, \( \text{mean}_{\text{tumor}} / \text{mean}_{\text{muscle}} \) were calculated.

**Histologic and immunohistochemical analysis**
Formalin-fixed, paraffin-embedded sections (5 μm) of resected tumor tissue were dewaxed, rehydrated, and micro-waved for 30 minutes at 0.01 mol/L citrate buffer, pH 6.0 containing 0.1% Tween 20. Sections were washed in TBS (pH 7.6) containing 5% fetal calf serum (Life Technologies) for 20 minutes. The primary antibodies used were: anti-Ki-67 antigen antibody solution (MIB-1, M7240, Dako; 1:75 diluted with Antibody Diluent (Dako ChemMate), anticleaved caspase-3 rabbit antibody solution (Asp175, Cell Signaling). The remainder of the procedure was carried out on the automated immunostainer (DISCOVERY XT, Ventana Medical System). Diaminobensidine (Ventana Medical System) liquid served as chromogen.

**Statistical analysis**
Statistical analyses were conducted using the statistical function of Excel 2007 (Microsoft) or GraphPad Prism 5 (GraphPad Software). A P value < 0.05 was considered statistically significant as assessed by t test.

**Results**
**FLT uptake is a sensitive measure for HSP90 inhibition of NPM-ALK+ ALCL in vitro**
SUDHL-1 ALCL cells depend on the constitutive activity of the ALK kinase that results from the NPM-ALK t(2;5)(p23q35) translocation (23, 22). Complex formation of NPM-ALK with HSP90 is critical to prevent degradation of the oncoprotein (26). Using MTT assays, SUDHL-1 cells showed sensitivity to a 48 hours treatment with the HSP90 inhibitor AUY922 with a maximum effect at the 100 nmol/L dose level and an IC₅₀ of less than 10 nmol/L (Fig. 1A). PI staining revealed that AUY922 induced both cell cycle arrest and cell death as showed by a significant decrease of the S phase fraction and a marked increase of the G₀–G₁ fraction as well as a higher number of AnnexinV-positive cells (Fig. 1B). In the presence of AUY922, expression of phosphorylated and total NPM-ALK was dramatically reduced in a dose-dependent manner after 48 hours (Fig. 1C). Moreover, the downstream signaling molecules STAT3 and AKT (24) as well as their phosphorylated forms were virtually undetectable at the 50 nmol/L dose level. To estimate whether HSP90-NPM-ALK-targeted treatment with AUY922 was assessable by measuring FDG and FLT uptake, we determined the cellular tracer uptake of FLT and FDG in AUY922 treated cells. SUDHL-1 cells were incubated with FLT or FDG for 45 minutes after a 48-hour treatment period and the activity was measured using a gamma-counter. HSP90 inhibition led to a significant reduction of both FLT and FDG uptake in SUDHL-1 cells (Fig. 1D). However, sensitivity of FLT was significantly higher showing a complete lack of FLT uptake in the presence of 25 nmol/L AUY922. In contrast, FDG uptake was only reduced by 40% compared with the vehicle-treated control at the same dose level. These \( \text{in vitro} \) results were confirmed by the additional analysis of the NPM-ALK positive ALCL cell lines JB-6 and SR-786 and murine B cells expressing ectopic NPM-ALK. Although these cells were sensitive to AUY922 treatment to various extents, early response monitoring revealed superiority of FLT as a tracer more than FDG (Supplementary Fig. S1A–S1C). These data suggest that FLT might be a suitable tracer particularly to determine effective NPM-ALK-targeted treatment \( \text{in vitro} \).

**Functional in vivo imaging of response to HSP90 inhibition in SUDHL-1 Lymphoma by FLT-PET is superior to FDG-PET**
To evaluate FDG- and FLT-PET imaging for early response monitoring \( \text{in vivo} \), we generated xenograft SUDHL-1 tumors. To mimic the clinical situation treatment was initiated once tumor volume reached approximately 500 mm³. The control group showed a 3-fold (\( n = 4 \), mean 3.0-fold, SD = 1.5, range
2.1–5.6-fold) increase in tumor volume (Fig. 2A). In contrast, tumors of AUY922-treated mice remained nearly constant during the observation period (n = 12, mean 1.3-fold increase, SD = 0.3, range 0.7–1.7-fold). Notably, extended treatment beyond 14 days resulted in a slight reduction of the tumor volume in 3 mice (mean 0.8-fold, SD = 0.3, range 0.7–1.1-fold; data not shown). To determine the predictive value of early functional imaging for response assessment, we conducted FDG- and FLT-PET scans before and 5 days after initiation of AUY922 treatment. To do so, change of TBR on day 5 compared with pretreatment TBR, which was defined as 100%, was calculated (relative TBR). FDG-PET analysis of control animals revealed a significant increase in FDG uptake on day 5 (n = 4, mean 2.1-fold increase, SD = 0.7, range 1.9–3.3-fold, P = 0.03, Fig. 2B). In AUY922 treated animals, relative TBR of early FDG-PET did not show a significant reduction compared with the pretreatment control (n = 12, mean TBR 87%, SD = 40.3%, range 31–161%; P = 0.151). Interestingly, the mean TBR of FDG uptake at later time points (day 15–21) decreased to 44% (n = 3, SD = 33.6%, range 23–85%; data not shown). In contrast to FDG assessment, the relative mean TBR of FLT uptake decreased significantly to 40% compared with baseline (n = 12, SD = 20.7%, range 32%–67%, P = 0.001) as early as 5 days after initiation of therapy (Fig. 2C). The relative TBR of untreated controls increased to more than 200% during the same time period (n = 4, mean 2.1-fold increase, SD = 0.6, range 1.6–3.0-fold, P = 0.01). Later time points within the treatment group (day 15–21) did not show any further reduction in FLT uptake (data not shown). To correlate the PET findings with the treatment effects of AUY922 on SUDHL-1 xenograft lymphomas, we stained fixed tumor sections for the proliferation marker Ki-67 and cleaved caspase-3 to analyze apoptosis. AUY922 treatment led to a significant increase in apoptosis as quantified by cleaved caspase-3 positive cells (Fig. 2D, n = 5, mean 6.1%, SD = 3.5%) compared with untreated mice (n = 4, mean 1.6%, SD = 1.1%; P = 0.04). Moreover, the percentage of proliferating cells was substantially decreased by AUY922 as measured by Ki-67 staining with a mean of 15.3% (SD = 0.8%) for the treated and 63.3% (SD = 7%) for the control tumors (P = 0.03). Taken together, both FDG as well as FLT uptake correlates with response to HSP90 inhibition in vivo. However, FLT-PET is highly superior to FDG-PET for early in vivo response assessment that precedes the change of tumor volume.

**Functional imaging of mTOR inhibition in ALCL xenografts by FLT-PET is superior to FDG-PET**

To confirm the predictive value of FLT-PET imaging for early response evaluation using targeted agents, we treated mice bearing SUDHL-1 xenograft tumors with the mTOR inhibitor everolimus, and evaluated the efficacy of FDG- and FLT-PET monitoring. NPM-ALK-positive cells have previously been shown to undergo cell cycle arrest and apoptosis upon mTOR inhibition (27). Again, treatment was started when mice had measurable tumors. As depicted in Fig. 3A, tumor growth was completely inhibited by everolimus (mean 1.2-fold increase, SD = 0.6, range 1.6–3.0-fold, P = 0.01). Later time points within the treatment group (day 15–21) did not show any further reduction in FLT uptake at later time points (day 15–21) decreased to 44% (n = 3, SD = 33.6%, range 23–85%; data not shown). In contrast to FDG assessment, the relative mean TBR of FLT uptake decreased significantly to 40% compared with baseline (n = 12, SD = 20.7%, range 32%–67%, P = 0.001) as early as 5 days after initiation of therapy (Fig. 2C). The relative TBR of untreated controls increased to more than 200% during the same time period (n = 4, mean 2.1-fold increase, SD = 0.6, range 1.6–3.0-fold, P = 0.01). Later time points within the treatment group (day 15–21) did not show any further reduction in FLT uptake (data not shown). To correlate the PET findings with the treatment effects of AUY922 on SUDHL-1 xenograft lymphomas, we stained fixed tumor sections for the proliferation marker Ki-67 and cleaved caspase-3 to analyze apoptosis. AUY922 treatment led to a significant increase in apoptosis as quantified by cleaved caspase-3 positive cells (Fig. 2D, n = 5, mean 6.1%, SD = 3.5%) compared with untreated mice (n = 4, mean 1.6%, SD = 1.1%; P = 0.04). Moreover, the percentage of proliferating cells was substantially decreased by AUY922 as measured by Ki-67 staining with a mean of 15.3% (SD = 0.8%) for the treated and 63.3% (SD = 7%) for the control tumors (P = 0.03). Taken together, both FDG as well as FLT uptake correlates with response to HSP90 inhibition in vivo. However, FLT-PET is highly superior to FDG-PET for early in vivo response assessment that precedes the change of tumor volume.

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0.7, range 0.5–2.3-fold), whereas the size of control tumors steadily increased over time (mean 5.6-fold, SD 
= 1.6). By using FDG-PET only a marginal, nonsignificant reduction of tracer uptake could be observed 5 days after therapy initiation compared with pretreatment values (Fig. 3B). Although everolimus-treated tumors revealed less FDG uptake compared with control tumors, this difference did not reach statistical significance. In contrast, FLT-PET significantly discriminated between control and treatment group (Fig. 3C). We also found a modest, but statistically significant reduction of FLT uptake before and after initiation of everolimus application (P = 0.01). Treated tumors harbored more cleaved caspase-3-positive cells compared with controls (Fig. 3D, 6.2% vs. 2.2%, P = 0.04). Notably, exposure to everolimus dramatically decreased the percentage of Ki-67-positive cells from 57.1% to 20.3% (P < 0.0001). Thus, functional imaging with FLT-PET rather than FDG-PET has a predictive value for response to mTOR inhibition.

These in vivo results were substantiated by further in vitro studies. Using MTT assays, we observed a reduction of cell growth to approximately 20% after incubation with 1 nmol/L everolimus for 48 hours compared with untreated cells (Supplementary Fig. S2A). At the same dose level, PI staining revealed a 50% decrease of cells in S phase and a marked increase of cells in G0–G1 phase (Supplementary Fig. S2B), whereas the sub-G1 subset (Supplementary Fig. S2B) and the AnnexinV-positive fraction (Supplementary Fig. S2C) was low. In vitro efficacy could also be showed by immunoblot analysis showing an abrogation of p70S6 kinase phosphorylation at a dose as low as 1 nmol/L (Supplementary Fig. S2D). In contrast to everolimus-responsive SUDHL-1 cells, other human ALCL cell lines that did not respond to everolimus treatment (defined...
as a reduction of S phase percentage or increase in apoptotic cells) showed no decrease in FLT uptake, again correctly predicting resistance. FDG-uptake correlated with cell cycle analysis and Annexin staining only in one cell line (Ba/F3-NA; Supplementary Fig. S3A–S3C).

Validating the predictive value of FLT-PET imaging for therapy monitoring in vivo

To evaluate the selectivity of FLT-PET to predict response to targeted therapy, we used a different NPM-ALK expressing lymphoma cell line, Karpas299. Differently from SUDHL-1 ALCL cells, Karpas299 ALCL cells gave rise to xenograft tumors that were entirely resistant to targeted therapy with AUY922 (n = 10, mean 3.2-fold increase, SD = 0.4, range 2.9–3.6), resulting in a similar growth rate as control tumors (n = 7, mean 5.2-fold increase, SD = 1.5, range 2.8–7.6; Fig. 4A). In contrast, everolimus treatment (n = 8, mean 1.0-fold increase, SD = 0.2, range 0.9–1.2) abrogated further Karpas299 tumor growth. FLT-PET scans were conducted before and 2 days after initiation of therapy and relative TBRs of each treatment group were calculated. As expected, relative TBR of FLT uptake of both control and AUY922-treated animals did not differ from each other (P = 0.42, Fig. 4B) and increased to a mean of 154% (range 107%–202%; SD = 35.5%) and 149% (range 46%–175%, SD = 47.2%), respectively. Most importantly, FLT-PET imaging showed a significant decrease of the relative TBR of everolimus-treated Karpas299 tumors compared with the respective control (mean 92%, SD = 37%, range 44%–163%, P = 0.001).

Figure 3. Functional in vivo imaging of mTOR inhibition in SUDHL-1 ALCL xenografts by FLT-PET is superior to FDG-PET. Mice were treated with everolimus (n = 12, 5 mg/kg orally daily) or glucose 5% (n = 7, p.o. daily) when xenotransplants reached a volume of approximately 500 mm³ (day 0). Some mice were sacrificed to explant lymphomas for immunohistochemical analysis (everolimus group: n = 6, day 5; control group: n = 4, day 11–14) and remaining animals were monitored for tumor growth until day 14. A, tumor growth in everolimus-treated and control mice. FDG-PET (B) and FLT-PET (C) were conducted before (day 0) and 5 days after therapy initiation. Left panels, representative PET scans showing change of tumor tracer uptake (arrows). Right panels, TBR was calculated and served as an indicator of tracer uptake. TBR on day 0, defined as 100% (pre), and change of TBR compared with pretreatment values are shown for treated (post) and control animals. Mean TBR of FLT-PET was significantly reduced in contrast to TBR of FDG-PET. D, IHC of explanted lymphomas using the apoptosis marker cleaved caspase-3 and the proliferation marker Ki-67.

A–D, mean ± SD is shown.
again correctly predicting tumor growth kinetics. Thus, FLT-PET seems to be suitable to discriminate very early between response and resistance to targeted therapy. The PET findings were confirmed by immunohistochemistry (IHC). Compared with vehicle, everolimus induced a significant increase of apoptosis as detected by caspase-3 staining (Fig. 4C, mean = 12.3%, SD = 2.2% vs. mean = 0.8%, SD = 0.04%, P = 0.02). In contrast, no significant induction of apoptosis was detected after AUY922 treatment compared with control tumors (mean = 1.0%, SD = 0.5%, P = 0.5). In addition, the percentage of Ki-67 positive cells was significantly reduced after treatment with everolimus (Fig. 4D, mean = 37.1%, SD = 2.3%) in contrast to control tumors (mean = 59.9%, SD = 5.6%, P = 0.02), indicating a strong induction of cell cycle arrest. AUY922 also led to a slight reduction of Ki-67 staining, however not to the level of statistical significance (mean = 45.1%, SD = 3.1%, P = 0.1). Taken together, these data strongly support superiority of FLT-PET imaging for response prediction in vivo, thus allowing an early distinction between sensitive and refractory disease.

Because Karpas299 ALCL cells were not responsive to HSP90 inhibition by AUY922 treatment but sensitive to mTOR inhibition by everolimus in vivo, we assessed the effect of both drugs on Karpas299 cells in vitro. Karpas299 cells were
exposed to escalating doses of AUY922. After a treatment period of 48 hours cell cycle distribution was analyzed by PI staining. Figure 5A shows that AUY922 had virtually no effect on cell cycle distribution. In accordance with the in vivo data, Karpas299 were sensitive to everolimus treatment resulting in an approximately 50% reduction of cells in S phase compared with control cells (Fig. 5A), although apoptosis was not increased (Fig. 5B). To evaluate the distinct biologic effects of HSP90 and mTOR inhibition, we analyzed the biochemical effects by immunoblotting (Fig. 5C). Consistent with the PI staining and xenograft results and in sharp contrast to SUHDL-1 cells, HSP90 inhibition did not downregulate ALK phosphorylation or ALK protein levels. Moreover, the downstream targets phospho-Akt and Akt levels as well as phospho-STAT3 and STAT3 levels were virtually unchanged upon AUY922 treatment up to concentrations of 50 nmol/L and 100 nmol/L, respectively. Importantly, incubation of Karpas299 cells with everolimus abrogated

Figure 5. Concordance between cell cycle state and pathway inhibition. Karpas299 cells were cultured with AUY922 or everolimus as indicated for 48 hours. A, cell cycle distribution assessed by PI flow cytometry. The top panels show representative DNA histograms; the bottom panels show quantification from \( n = 3 \) experiments. The bars represent the mean ± SD. B, assessment of apoptosis by AnnexinV (AnnV) flow cytometry. The top panels show representative dot blot analyses; the bottom panels show the mean ± SD \( (n = 3) \). C, validation of target inhibition by immunoblotting was conducted using the indicated antibodies. Cell cycle distribution and NPM-ALK signaling was not affected by AUY922 (A, left; C, left). In contrast, everolimus induced G1 arrest with consecutive reduction of cells entering S phase (A, right). In addition, phosphorylation of the mTOR downstream target protein p70S6 kinase (p70S6K) was completely abrogated at concentrations as low as 1 nmol/L (C, right).
the phosphorylation of the mTOR downstream target p70S6 kinase at the same dose level (1 nmol/L) compared with SUDHL-1 cells (Fig. 5C). These data indicate a strong concordance between early response evaluation by FLT-PET in vivo, tumor growth in vivo, and effective in vitro pathway inhibition. Our studies thus provide strong evidence that FLT-PET appears to be highly suitable to predict early response to targeted therapy in vivo.

Discussion

Ongoing progress in the understanding of lymphoma pathogenesis leads to the large-scale development of a multitude of pathway targeting drugs (29, 30). To optimize design and interpretation of clinical trials it will be crucial to identify biomarkers of sensitivity and response. These markers will also accelerate validation of effective drug combinations in the preclinical setting. Although pharmacodynamic biomarkers assess target inhibition and pathway downregulation, this does not necessarily equate with clinical benefit (31). In addition, many biomarker assays have been neither standardized nor validated (32). Thus, it is unlikely that in the majority of patients with advanced lymphoma the mere presence of a biomarker, a genetic profile, or an activated pathway will suffice to predict response to targeted therapy. Functional in vivo imaging could therefore be useful to assess and predict response to a specific treatment very early upon treatment initiation, at a time point, when conventional imaging cannot be expected to detect either response or resistance.

Our studies used the molecularly defined lymphoma entity ALCL, characterized by ALK-dependent pathway activation, to functionally evaluate the standard PET tracer FDG and the thymidine analogue FLT as early response markers. Constitutive ALK activation is a characteristic of NPM-ALK positive lymphoma and results in the activation of PI3K-AKT-mTOR and JAK-STAT signaling. Both are critical survival and proliferation pathways and have been proposed as pharmacologic targets for malignant diseases including lymphoma (24, 33, 34). On the basis of the defined oncogene and subsequently deregulated signal transduction, we felt that these lymphoma cells are most suitable for a translational approach comprising both in vitro and in vivo assays. HSPP90 has been identified as an attractive target for anticancer therapy, because its inhibition effectively induced apoptosis in ALK+ ALCL through the accelerated degradation of NPM-ALK and other proteins (26, 35). Everolimus is an approved mTOR inhibitor that has also shown efficacy in numerous tumors (36). We show that FLT uptake by lymphoma cells during inhibition of NPM-ALK or NPM-ALK downstream pathways closely reflected antiproliferative response. Moreover, there was a strong correlation between in vivo and in vitro results including Western blot analyses assessing the activation of NPM-ALK and NPM-ALK-dependent pathways. Most importantly, early changes of TBR of FLT+, but not FDG-PET, preceded change of tumor volume thus allowing distinction between sensitive and resistant cell lines and prediction of therapy response.

FDG-PET after completion of therapy is the noninvasive modality of choice for response classifications of aggressive lymphomas (5). About interim FDG-PET during lymphoma treatment recent clinical studies investigating its predictive value have clearly attenuated the validity in this scenario (10, 37). Moreover, FDG-PET did not predict tumor response during mTOR inhibition both in patients with advanced solid tumors and murine xenograft models (38) emphasizing the need for new surrogate markers reflecting early antiproliferative rather than metabolic response. FLT has been shown to accumulate in a variety of tumor entities because of intracellular trapping upon phosphorylation by the S phase enzyme thymidine kinase 1 (TK1; 13, 15, 16, 17). The correlation between TK1 activity and cellular uptake renders FLT an excellent surrogate marker of proliferation (14).

The lack of FDG to reflect tumor response early after initiation of HSP90 or mTOR-targeted therapy is in accordance with results from other preclinical models for breast (39, 40), ovarian (41), and pancreatic cancer (38). It is likely that an influx of inflammatory cells, which can be observed already 48 hours after mTOR inhibition (42), contributes to higher FDG-uptake in vivo. Because FDG-uptake of inflammatory cells is similar or may even exceed that of tumor cells, transient increase in stromal reaction may result in overestimation of viable tumor (43). The observed dispersion of FDG uptake might also be attributed to a variable degree of inhibition of glycolysis as a consequence of disruption of the AKT-pathway resulting in altered FDG uptake (38, 44). On the contrary, FLT uptake has been proven as a valid imaging biomarker for abrogation of the PI3K-AKT-mTOR pathway in solid tumors (41, 45). Inhibition of the NPM-ALK downstream pathway is known to induce cell-cycle arrest in G1 phase because of increase of p27 and decrease of cyclin D1 expression, a state resulting in low-TK1 activity (46). Being a substrate of TK1, FLT thus appears as the ideal surrogate marker for inhibition of this pathway. Consistently, we observed a significant reduction of FLT uptake on day 5 after commencement of both HSPP90 and mTOR inhibition as measured by TBR of FLT-PET. Effective targeting was validated by documentation of tumor growth and immunostaining of explanted lymphomas, which revealed both a significant reduction of the proliferation and an increase of apoptosis.

Of note, we found a significant increase of apoptosis in lymphomas treated with everolimus in vivo, but not in vitro. This gives rise to the hypothesis that not only targets within the tumor cell, but also within the microenvironment of the tumor seem to contribute to tumor control. Indeed, everolimus potently inhibits growth of stromal and endothelial cells in vitro and reduces tumor vascularization in vivo (47). However, PET monitoring of antiangiogenic effects of everolimus failed both with FDG- and FLT-PET in several tumor entities (48). These observations as well as the fact, that inhibition of cell proliferation can be a transient phenomenon in the setting of intermittent drug administration (41, 42) underline the importance of careful consideration of pharmacodynamics in designing imaging protocols for response assessment.
Here we present a translational study including molecular, cellular, as well as in vivo analyses to validate the predictive value of PET for early assessment of response to targeted treatment. Our data provide strong evidence that FLT, but not FDG uptake represents a reliable, noninvasive surrogate marker to distinguish between sensitive and resistant lymphoma early after treatment initiation. These findings will facilitate rapid preclinical and clinical evaluation of novel inhibitors targeting this pathway.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

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Conception and design: Z. Li, N.A. Graf, K. Herrmann, M. Schwaiger, A. Buck, U. Keller, T. Dechow
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Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): Z. Li, N.A. Graf, K. Herrmann, A. Jünger, A. Walch, M. Schwaiger, T. Dechow

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FLT-PET Is Superior to FDG-PET for Very Early Response Prediction in NPM-ALK-Positive Lymphoma Treated with Targeted Therapy

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