Preclinical Modeling of a Phase 0 Clinical Trial: Qualification of a Pharmacodynamic Assay of Poly (ADP-Ribose) Polymerase in Tumor Biopsies of Mouse Xenografts

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Abstract

Purpose: The National Cancer Institute has completed a first-in-human clinical pharmacodynamic trial of the targeted agent ABT-888, a poly (ADP-ribose) polymerase (PARP) inhibitor, under the auspices of the U.S. Food and Drug Administration's Exploratory Investigational New Drug Application. Performance of the study design, needle biopsy procedure, and validated pharmacodynamic assay were evaluated in human tumor xenograft models.

Experimental Design: A validated ELISA was used to quantify PAR, a product of the PARP 1/2 enzyme activity. Sampling variability from tumor heterogeneity was determined by comparing PAR content in multiple tumors, and in different areas of the same tumor in a particular animal, collected under anesthesia by needle biopsy or resection before and after administration of nontoxic doses of ABT-888. The degree of PARP inhibition following single-dose treatment was evaluated in the time frame anticipated for biopsy in humans.

Results: Sampling variability around the mean (~50%) for untreated and vehicle-treated animals was random and due to specimen heterogeneity. PAR levels in initial and repeat tumor biopsies, separated by 1 week, were not altered by the stress induced by daily handling of the animals. A single ABT-888 dose (3 or 12.5 mg/kg) reduced intratumor PAR levels by >95%. ABT-888 (1.56-25 mg/kg) significantly decreased PAR levels at 2 h post-dosing.

Conclusion: The detailed methodologies developed for this study facilitated the design of a phase 0, first-in-human clinical trial of ABT-888 and could serve as a model for developing proof-of-principle clinical trials of molecularly targeted anticancer agents.

Barely 5% of all investigational new drug applications for novel molecular agents in oncology advance from the investigational phase to registration (1). Questionable interpretation and validation of existing preclinical models for early-phase clinical trials may contribute to this statistic. Furthermore, early-phase trials rarely incorporate robust pharmacodynamic assay methodologies designed to measure a drug's effect on its presumed target. Pharmacodynamic assays can provide critical information on the probability of a drug's overall success in advancing through the developmental pipeline and could be very useful in eliminating future clinical failures. A pharmacodynamic assay that provides meaningful scientific results can also preclude exposing study participants to invasive procedures unnecessarily. Thus, "humanizing" preclinical models with validated pharmacodynamic assays and clinically relevant methodologies for tissue sampling, coupled with better statistical design and analysis, could substantially...
Translational Relevance

This article shows how “humanizing” preclinical models with validated pharmacodynamic assays and clinically relevant methodologies for tissue sampling, coupled with better statistical design and analysis, can substantially improve early-phase clinical trials. Pharmacodynamic assays provide critical information on whether an investigational agent acts on its presumed target; this knowledge is invaluable to evaluate the probability of an agent’s overall success in advancing through the clinical development pipeline. This report describes the use of a validated pharmacodynamic assay to support the design of a proof-of-principle, first-in-human, phase 0 clinical trial of the molecularly targeted anticancer agent ABT-888. Assessing the analytical performance of a validated assay in preclinical models using clinically relevant procedures is essential to show that the assay is clinically ready and thus satisfy review boards that pharmacodynamic results (e.g., minimal biologically effective dose) can serve as the clinical trial’s primary endpoint. These critical evaluation procedures distinguish the development of an assay for a phase 0 trial from the correlative studies generally included as secondary endpoints in early-phase clinical trials.

Materials and Methods

Xenograft models

Cell lines. Cells were purchased from the American Type Culture Collection and grown in humidified incubators supplemented with 5% CO2; the cell culture medium was maintained according to the American Type Culture Collection recommendations. The assay controls were produced from the Colo829 tumor cell line and grown to superconfluence in T75 flasks. After washing in HBSS, cells were harvested by scraping in lysis buffer (Biosource) supplemented with protease inhibitor cocktail tablets (Roche Applied Science) and 1% phenylmethylsulfonyl fluoride (Sigma-Aldrich). Cell culture medium and regents were purchased from Invitrogen.

Animals. Xenografts were established in female athymic nu/nu (NCr) mice (National Cancer Institute Animal Production Program).

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Improve early-phase clinical trials. This philosophy is critical to the success of clinical pharmacodynamic trials in oncology.

The National Cancer Institute has initiated a series of phase 0 trials under the purview of an exploratory investigational new drug application from the U.S. Food and Drug Administration to explore their value in accelerating clinical evaluation of investigational agents in oncology. Some phase 0 trials will be designed to evaluate the pharmacodynamic effects of nontoxic doses of new agents at a molecular level; tumor biopsies and established surrogate tissues determine whether an investigational agent acts on its presumed target, thus providing evidence for its mechanism of action and pharmacological properties. Essential to this process is a pharmacodynamic assay that has been validated for analytical performance and proven to be therapeutically relevant in preclinical studies. Rigorous proof of clinical readiness is predicated on preclinical data showing drug effectiveness as measured in repeat tumor biopsies, a drug time-effect window that is clinically feasible to study, and some insight into the drug exposure likely to produce a measurable pharmacodynamic effect.

Furthermore, questions that have confounded the interpretation of correlative studies in phase I and II trials can be answered because they affect the primary endpoint of a phase 0 trial, for example, whether clinical assessment of drug action can be better assessed by comparing biopsies from two lesions or sequential biopsies of the same lesion.

Poly (ADP-ribose) polymerase (PARP) detects and facilitates repair of single-stranded DNA breaks; expression is up-regulated in tumor cells possibly as a mechanism to escape apoptosis. PARP activity is also important in inflammation, necrosis, and apoptotic pathways in the presence of DNA damage. Thus, PARP inhibitors are being investigated for several disease indications. Theoretically, inhibition of PARP via small-molecule agents such as ABT-888 (NSC 737664) should sensitize tumor cells to a variety of cytotoxic drugs and radiation. In a series of recent studies, ABT-888 potentiated treatment with temozolomide, platinum-containing agents, cyclophosphamide, irinotecan plus temozolomide, topotecan, indenoisoquinolines, camptothecin, and ionizing radiation in peripheral blood mononuclear cells and syngeneic and xenograft tumor models. The product of PARP 1/2 enzymatic activity, PAR, was selected as a pharmacodynamic endpoint in the current study in an effort to minimize complicating factors associated with measuring drug activity by enzyme assays of tissue extracts. Specimen collection and handling methods were also designed to stabilize PAR, allowing measurement of PARP activity inside the target tissue at the time of tissue excision.

Our laboratory has developed and cross-validated an enzyme immunoassay, in collaboration with Abbott Laboratories and the National Clinical Target Validation Laboratory at the National Cancer Institute, to measure PAR levels in human tumor xenograft models and in peripheral blood mononuclear cells isolated from healthy human subjects; assay validation details are provided with the Supplementary Materials of this report. Preclinical modeling of the planned phase 0 trial design tested whether nontoxic doses of ABT-888 would result in a statistically significant reduction of PAR levels in tumor needle biopsies despite sampling variability due to intratumor and intertumor heterogeneity. The phase 0 clinical protocol was mirrored in the current preclinical study in athymic nude [nu/nu (NCr)] mice bearing Colo829 and A375 human tumor (melanoma) xenografts by using clinical procedures for collecting needle biopsies over a time frame achievable in the clinical setting and by implementing standard operating procedures for specimen handling and storage transferable to a clinical laboratory. Intertumor and intratumor variability of PAR levels was assessed in both needle biopsies and resected tumors of live animals under general anesthesia, including biopsies from two different tumor nodules in the same animal. Stability was also evaluated between repeat biopsy procedures separated by 1 week. The dose and time effect of ABT-888 on PAR levels in tumor samples established the minimum dose required to elicit a pharmacodynamic effect and the optimal time after drug administration to schedule a biopsy for pharmacodynamic assessment in the phase 0 clinical trial. Preclinical modeling not only informed the design of the trial but also served as a useful preclinical paradigm for developing future clinical pharmacodynamic studies of molecularly targeted anticancer agents.
with the human melanoma cell lines A375 and Colo829 by s.c. injection (1.0 × 10^7 cells per 0.1 mL/mouse) on the lateral body wall, just caudal to the axilla. All mice developed tumors, and the tumors were maintained by serial in vivo passage using tumor fragment transplantation when the donor tumors reached 10 to 15 mm in diameter. Tumors were staged to a preselected size (weight) using the following formula: weight (mg) = (tumor length × tumor width^2) / 2 (17). Mice were housed in sterile, filter-capped, polycarbonate cages (Allentown Caging) maintained in a barrier facility on a 12-h light/dark cycle and were provided sterilized food and water ad libitum (17). Mice were randomized before initiation of treatment using a commercial software program (StudyLog).

National Cancer Institute-Frederick is accredited by Association for Assessment and Accreditation of Laboratory Animal Care International and follows the USPHS Policy for the Care and Use of Laboratory Animals. Animal care was provided in accordance with the procedures outlined in the "Guide for Care and Use of Laboratory Animals" (National Research Council, 1996; National Academy Press). All the studies were conducted according to an approved animal care and use committee protocol.

Study agents. ABT-888 (NSC 737664; Abbott) was solubilized to the required strength, not exceeding 5 mg/mL, in a clinically relevant vehicle consisting of sorbitol (105 mg/mL) and citric acid (monohydrate; 5.17 mg/mL) in sterile water. ABT-888 was administered orally by gavage as a single 3 or 12.5 mg/kg dose. Dose volume was defined as 0.1 mL/10 g body weight. Topotecan was administered i.p. at the single vehicle consisting of sorbitol (105 mg/mL) and citric acid (mono-hydrate; 5.17 mg/mL) in sterile water.

Tumor biopsies. When surgical anesthesia was reached (no toe pinch), the skin was disinfected with Nolvasan (Fort Dodge Lab) and a 1 to 5 mm incision was made through the skin adjacent to the s.c. tumor being biopsied. An approved human biopsy needle (Temno 18-gauge; Allegiance Healthcare) was passed through the skin incision into the tumor. Once the needle was maximally in the tumor, a biopsy was collected, and the biopsy needle was retracted. The collected material (~1 × 5 mm) was immediately flash frozen in an O-ring sealed, screw-capped, Sarstedt cryovial by touching the biopsy to the inside of the vial that was precooled in liquid nitrogen (a critical step for stabilizing specimen PAR content). The vial was then sealed and returned to liquid nitrogen. Frozen specimens were stored at -80°C until use. After sample collection, the wound was closed with a surgical wound clip. Biopsies were done at baseline/0, 2, 4, 7, and 24 h after dosing. Repeat biopsies in untreated animals were separated by a 1-week recovery period, during which time animals were handled daily to model patient assessment anticipated during the clinical trial. Standard operating procedures were developed for stabilizing PAR content in the needle biopsies using the tumor xenograft models in an interventional radiology setting.

Tumor resection. Xenograft tumors were collected on the same schedule as tumor biopsies by standard dissection methods. Specimens were left intact or cut into two to four equal pieces with fine-point scissors and placed into Sarstedt microfuge tubes that were precooled in liquid nitrogen as described above.

Tumor extract preparation. All tissue samples were processed by adding lysis buffer to the frozen tissue (0.5 mL/biopsy). Tissue was minced with fine-point scissors, vortexed, minced and vortexed again, and then kept on an ice bath. Extracts were disrupted by sonication, vortexed, allowed to stand in an ice bath for 15 min, vortexed again, and then supplemented with 1% SDS by adding 20% SDS concentration (Ambion). Specimens were vortexed and then immersed in a boiling water bath for 5 min; subsequently, they were snap-cooled for 1 min in an ice bath and then moved to ambient temperature. After vortexing again, specimens were clarified by centrifugation at 10,000 × g for 2 min at 4°C. Specimens could be subjected to at least three freeze-thaw cycles without a detectable loss of antigen binding.

Statistical analysis. Regression analysis and descriptive statistics were conducted with Microsoft Excel. The significance level for the 95% confidence interval (95% CI) was set at 5% (x = 0.05) for a one-sided test. In this study, coefficient of determination (R^2) values <0.55 were considered random, whereas all higher values were indicative of systematic variability [the correlation coefficient (R) >0 at the one-sided, x = 0.05, significance level]. This was justified by the fact that, for a data set of 6 pairs (n = 6), R = 0.74 (the square root of 0.55) was the smallest R, such that the lower 95% CI bound was >0 by use of Fisher’s transformation (18). A value of 0.74 was considered appropriate for all comparisons, even for those involving 12 data pairs, because there were only 6 animals. A one-sided significance level was appropriate because all correlations were expected to be nonnegative. Also, an R^2 value of 0.55 indicated that 55% of the variation associated with either of the two variables was accounted for by the linear fit to the other variable.

Throughout this article, error bars for individual tumor measurements are not visible because they are covered by the symbols on the graphs. Thus, the significant variability in PAR values between two tumors within a particular animal was due to local or regional differences in xenograft composition plus any differences in PAR preservation through the tissue collection and extraction steps.

Biomarker development

Assay methodology. The PAR immunoassay uses a purified monoclonal antibody (Clone 10H; Trevigen) to PAR as the capture reagent, and an anti-rabbit horseradish peroxidase conjugate reporter (KPL). Assay methodology and validation are detailed in the Supplementary Materials. Units of measure were pg/mL. PAR normalized to 100 ug/assay well protein load, abbreviated in the tables and figures as "PAR level." Assay validation. The PAR immunoassay was subject to a validation protocol for analytical performance (see Supplementary Materials).

Results

Random intertumor variability in PAR levels of untreated xenografts. Variability in PAR levels across resected tumors in individual animals was assessed in a bilateral tumor Colo829 xenograft model. Large (≥300 mg) and small (150-200 mg) tumors occurred randomly on the left and right flanks of the animal. Large tumors were included as a surrogate for degree of necrosis within individual tumors. Mean PAR content was 5,584 units (95% CI, 4,102-7,066 units) in the large tumors and 4,146 units (95% CI, 3,087-5,205 units) in the small tumors (Fig. 1A). PAR levels in extracts from one to two pieces of each tumor varied by a 5- and 4-fold margin in the large and small nodules, respectively. Variability in PAR levels was random (not systematic; R^2 < 0.55), and there was no correlation in PAR levels between the large and the small nodules in the individual animals.

Random intratumor variability in PAR levels of untreated xenografts. Experiments were conducted with both large and small tumors in the Colo829 xenograft model to determine whether intertumor variability of PAR levels was greater than intertumor variability. As with intertumor variability, large tumors were evaluated as a surrogate for levels of necrosis. Two quadrants (“first piece” and “second piece”) of each resected large and small tumor were selected for analysis. Random intratumor variability of PAR levels was observed from pieces of both large and small tumors (Fig. 1B and C). PAR levels in the first and second pieces of the large or small tumors were not significantly different (Supplementary Table S3). Four of the 24 tumors had PAR levels >6,000 units; these were all large...
Fig. 1. Intertumor and intratumor variability of PAR levels in untreated Colo829 xenografts. A, correlation in PAR levels between the large and small bilateral tumors of individual mice. B, correlation in PAR levels between two quadrants cut from each resected large tumor of the bilateral pair. C, correlation in PAR levels between two quadrants cut from each resected small tumor of the bilateral pair. Samples were collected 4 h post-dose. Values reported as pg PAR/mL normalized to 100 μg protein. Solid diamond, measured point; line, linear regression fit.

No systematic variability observed in PAR levels between extracts from biopsy samples and A375 tumor xenograft pieces. PAR levels in the biopsy specimens were compared with those in the residual tumor that was resected immediately after the biopsy procedure (Fig. 3). No systematic variability was detected in PAR levels between biopsies and tumor xenograft pieces ($R^2 = 0.001$). However, biopsy PAR levels were generally higher than those obtained from the corresponding resected tumor. Furthermore, the 5-fold range in PAR level variability across individual biopsies was not greater than that found in the excised tumor quadrants, indicating that a similar drug effect level will be required to show significant target inhibition using either the 18-gauge needle or excisional biopsy procedures. Thus, smaller specimen size did not increase sampling variability in PAR levels.

Although PAR levels in the A375 tumors were generally higher than in the Colo829 tumors, the variability in PAR levels observed with the needle biopsy procedure in untreated A375 xenografts was similar to that of Colo829 xenografts. PAR levels from the needle biopsies of A375 tumors implanted on the left or right flank showed large variations around the mean ($R^2 = 0.139$), which appeared to be random (Fig. 3B). Individual PAR values from A375 needle biopsies were not normally distributed around the mean (2 SDs below the mean resulted in negative PAR values). Acquiring A375 biopsy specimens was made difficult by the softness of the tumor tissue, especially with repeat biopsies. Low PAR values in all the panels were associated with higher levels of extract loaded into the immunoassay. Subsequent to this work, optimum protein load for assaying xenografts was determined to be 5 μg/well with a range of 1 to 10 μg/well. This proved to be a critical variable for the success of the assay. Analytical experiments indicated that the lower PAR levels at protein loads above 5 μg/well were associated with passive interference in the assay. High levels of cellular DNA (increasing extract viscosity) yielded a similar interference effect.

Repeat biopsy sampling produced random variability of PAR levels in A375 xenografts. A375 xenografts were used for comparing PAR levels in repeat 18-gauge needle biopsies of individual tumors, separated by a 1-week recovery period. Individual animals were handled during the 1-week interval to control for the effects of stress on PAR levels and attempt to replicate conditions encountered by phase 0 trial participants. No statistically significant effect was observed in PAR levels between the first biopsy and the second biopsy (first biopsy mean $\pm 95\%$ CI, 15,620 $\pm 7,245$; second biopsy mean $\pm 95\%$ CI, 17,703 $\pm 8,950$). Regression analysis of sequential biopsies failed to show a strong correlation between PAR levels and the biopsy sequence (Fig. 3C), showing random variation around the mean.

ABT-888-induced suppression of PAR levels was maintained over time in Colo829 xenografts. ABT-888 significantly decreased PAR levels 2 h post-dose in all treatment groups (Table 1). At the lowest dose of 1.56 mg/kg, ABT-888 significantly reduced PAR levels compared with the paired controls. Higher doses (12.5 mg/kg) suppressed PAR levels by >99%. After 5 h, significant suppression of PAR levels persisted in the
correlation in PAR response to ABT-888 was detected between large and small tumor PAR levels (Fig. 4A). No treated groups showed a modest correlation ($R^2 = 0.758$) in PAR levels below the nominal lower limit of quantitation (LLQ) of specimen from the smaller tumor at 12.5 mg/kg. PAR levels were suppressed >98% in small tumors at 3 mg/kg. All but one (see Table 2).

In other studies (data not shown). The apparent increase in mean PAR levels 2 h after topotecan dosing was not statistically significant but may be a real effect.

Similar dose-dependent reductions in PAR levels were observed in the first and second pieces cut from the excised large tumors at either the 3 or 12.5 mg/kg dose (Fig. 4B). The vehicle-treated group for excised large tumors was also considered to exhibit random variability. The higher coefficient of determination ($R^2 = 0.644$) was due to a single outlier, which drove the regression coefficient from the randomly clustered data points around the mean value of 4000 pg/mL per 100 µg protein.

The vehicle-treated group in small tumors again showed a stronger correlation than the ABT-888-treated groups (less random variability; $R^2 = 0.788$) in PAR levels between the first and second tumor pieces (Fig. 4C). Modest correlation ($R^2 = 0.741$) in PAR levels was also observed between the pieces from the same tumor in the animals treated with ABT-888 at the 3 mg/kg dose. The lack of apparent correlation in intratumor PAR levels at the 12.5 mg/kg dose ($R^2 = 0.008$) may be associated with nearly complete suppression of PAR levels in the specimens. Sampling variability in PAR levels detected at baseline and following a single dose of vehicle or ABT-888 relative to the magnitude of the drug effect dictates a pharmacodynamic response of 42% to 95% suppression to reach statistical significance.

Pharmacodynamic response to ABT-888 in needle-biopsy xenograft samples—dose-dependent suppression. Four hours following administration of 12.5 mg/kg ABT-888, PAR levels had decreased by 89% in the Colo829 model and 99% in the A375 model compared with the controls. The A375 model exhibited higher baseline tumor PAR levels than the Colo829 model (Supplementary Table S5). PAR levels in the control groups did not change significantly following vehicle or topotecan administration.

Discussion

To our knowledge, this study is unique in that it tested human procedures in mice to measure inhibition of a molecular target in xenograft tumors collected from living animals. Two human tumor xenograft models were used to evaluate the variability of PAR levels in tissue from surgically excised tumor pieces and biopsies, to test whether a single dose of ABT-888 could suppress PARP activity, and to evaluate dose-escalation effects of ABT-888 on PAR levels. Human melanoma cell lines Colo829 and A375 were selected for modeling based on January 6, 2018. © 2008 American Association for Cancer Research.
The feasibility of conducting a pharmacodynamic immunoassay of needle biopsy material also prompted an investigation of PAR levels recovered 24 h after a single dose of ABT-888. Use important clinically (allows sufficient travel time) and because imposed a 4- to 7-h post-dose sampling window, which is on the same day as drug administration. This time restriction trial plan, which specified that consenting patients be biopsied evaluate. Sampling was consistent with the phase 0 clinical live animal biopsy methods this model was designed to melanoma model; B16 tumors are not readily assessable by the experiments done at Abbott using the syngeneic mouse B16 xenografts. A375 values were reported as pg PAR/mL normalized to 100 μg protein. Solid diamond, measured point; line, linear regression fit.

Fig. 3. Correlation of PAR levels in A375 xenografts. A, PAR levels in 18-gauge needle biopsies versus surgically excised tumor pieces. Needle biopsies were collected from anesthetized animals, placed in pre-tared, precooled vials, and flash frozen in liquid nitrogen; the remaining xenograft was surgically excised and flash frozen. B, PAR levels in left versus right side tumors. Biopsies and tumor pieces (left versus right) from the same animal were graphed together. Data points represent either samples from needle biopsies or xenograft tumor pieces. C, first versus second repeat biopsy samples (collected from 16 xenografts in 8 animals). Values were reported as pg PAR/mL normalized to 100 μg protein. Solid diamond, measured point; line, linear regression fit.

on experiments done at Abbott using the syngeneic mouse B16 melanoma model; B16 tumors are not readily assessable by the live animal biopsy methods this model was designed to evaluate. Sampling was consistent with the phase 0 clinical trial plan, which specified that consenting patients be biopsied on the same day as drug administration. This time restriction imposed a 4- to 7-h post-dose sampling window, which is important clinically (allows sufficient travel time) and because PAR levels recover 24 h after a single dose of ABT-888. Use of needle biopsy material also prompted an investigation of the feasibility of conducting a pharmacodynamic immunoassay on limited tumor quantities. Wet-weight measurements from 18-gauge needle biopsies of Colo829 xenografts showed significant differences in the quantity of material recovered. Partial biopsies were associated with low weight because the needle passed completely through the tumor. Protein levels were also variable, probably reflecting the amount of plasma present as the animals were not perfused before sampling, a step omitted to mimic the clinical design.

The expected imprecision in PAR immunoassay results from all sources was quantified as <9%. This precision enabled a detailed analysis of the sources of variability encountered in the current experiments. For example, variability documented within different treatment and control groups could be attributed to the sampling method and inherent heterogeneity of the tumor itself, as most groups exhibited random variability ($R^2 < 0.55$). This trend was similar for both surgically excised tumor pieces and sequential biopsies. Higher PAR concentrations in biopsy samples than in tumor pieces were attributed to better preservation of the PAR antigen as biopsy samples freeze and thaw faster in lysis buffer and are more easily and rapidly extracted. Also, biopsy specimens were more readily solubilized by the extraction method than the tumor xenograft sections. The values obtained for the matched pairs of xenograft sections appeared to be as discrepant as the values obtained for treatment groups from different animals.

Although the variability observed in surgically excised tumor and sequential biopsy samples was random in most groups, an apparently higher ($R^2 > 0.55$), nonrandom correlation of PAR levels was observed in the vehicle-treated groups in contralateral tumors ($R^2 = 0.758$) and in large ($R^2 = 0.644$) and small ($R^2 = 0.788$) xenograft tumors. A possible explanation is that the high correlation was an artifact of the unusual heterogeneity of the groups, each containing one or two animals with very high levels of PAR, compared with the rest of the animals in those groups, thus driving the regression coefficient. A higher ($R^2 > 0.55$), nonrandom correlation of PAR levels was also measured within tumor pieces of the small xenograft tumors in the 3 mg/kg group ($R^2 = 0.741$), which was not directly attributable to an artifact of the methods employed. This value was significantly positive at the one-sided 95% CI ($\alpha = 0.01$ significance level); however, this somewhat isolated example of positive correlation between the samples from the same animal detected in a treated group must be viewed with some skepticism due to the other multiple analyses done showing different results. Baseline PAR levels also varied significantly in Colo829 xenografts between different experiments. PAR levels in the untreated and vehicle-treated groups varied in the same manner, and the means, SDs, and 95% CIs in those groups always overlapped, as was the case with PAR levels across experiments. Additional experiments have been planned to address whether the variability observed is inherent to the Colo829 model or whether it is associated with specimen storage.

Patients eligible to participate in oncology trials often have multiple tumors, presenting a dilemma to clinicians over whether to biopsy different lesions at baseline and post-dose or to biopsy the same lesion following a recovery period. These results illustrate the feasibility of re-biopsying the same lesion. The data also indicate that, at least in the xenograft models examined, the variation across PAR measurements from the same animal at different times or sites is comparable with the
variation across measurements from different animals. Therefore, little advantage may be gained from multiple pretreatment PAR measurements among individual tumor nodules or study participants. Decreases in PAR levels following ABT-888 treatment may have to be evaluated against the variation found in pretreatment PAR levels and across patients to determine statistical significance. Furthermore, the bilateral tumor model showed no bias in PAR measurements attributable to order of sampling or to the degree of necrosis or other features of tumor heterogeneity present in the xenografts.

The effect of a single dose of ABT-888 on PAR levels was impressive, with significant inhibition of PAR synthesis within 2 h at all dose levels tested. A strong tendency toward complete (>99%) inhibition of PAR levels was observed at the higher dose levels. By the 5-h time point, significant inhibition of PAR levels was detected only at the 12.5 and 25 mg/kg dose levels, and by 24 h, PAR levels had all recovered. These data suggest that the dose effects induced by 3 to 25 mg/kg doses of ABT-888 were distinguishable primarily by the duration of the response and not by the magnitude of inhibition observed.

Two technical aspects of tumor needle biopsy sample collection are essential to a successful pharmacodynamic study: (a) sampling variability that is sufficiently small at baseline (or in vehicle-treated groups) to show a drug-induced change in the target function and (b) a sufficiently low limit of quantitation in the validated assay to quantify a drug effect in a 1 to 2 mg tissue specimen. The high coefficients of variation around the means in the treatment groups (50% at high PAR levels to 150% at low PAR levels), regardless of the tissue collection procedure, have important implications for the design of

<table>
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<th>1.56</th>
<th>3.13</th>
<th>6.25</th>
<th>12.5</th>
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<td>18,029 ± 6,711</td>
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*All doses are mg/kg. n = 6 animals per group. Whole xenografts were surgically excised and half of the excised specimen was measured in the PAR immunoassay at protein loads of 10 to 20 μg/well. Single-dose topotecan was administered by i.p. injection as an additional control. Collection time points were selected to mimic the time points in the clinical trial. All units are pg PAR/mL per 100 μg protein. TPT, topotecan; LLQ, lower level of quantitation.

Table 1. Temporal effects of single-dose ABT-888 on PAR levels in Colo829 xenografts

Table 2. PAR levels in two quadrants (“first piece” and “second piece”) from resected large and small tumors of bilateral Colo829 xenografts treated with vehicle or ABT-888

* n = 6 animals per group. Two quadrants were dissected 4 h post-dosing from large or small xenografts, which occurred randomly in the right or left flank of each mouse.

† n = 6 animals per group × 2 tumors per animal × 1 half of each tumor (from large and small tumors).

‡ The modal value for this group was zero (12 of 24 specimens).

ABT-888 and vehicle were administered as a single dose. All units are pg PAR/mL per 100 μg protein; LLQ, lower level of quantitation.
clinical trials with ABT-888, as they predict the minimum amount of PARP inhibition necessary to achieve a statistically significant effect. Due to the high variability within treatment groups, at least a 50% inhibition of PAR levels was required to show a significant pharmacodynamic response to ABT-888 with statistical confidence. Therefore, the success of these modeling experiments was in no small measure due to the effectiveness of ABT-888 at inhibiting PAR synthesis in vivo.

The animal models presented in this study provided a good foundation for the design of the first oncology phase 0 clinical trial at the National Cancer Institute. Furthermore, the detailed evaluation of target variability and proof-of-principle concepts used in this study are important steps to complete before conducting any phase 0 trial, in which the pharmacodynamic endpoint serves as the primary objective, justifying the collection of biopsies from study participants. The availability of a validated immunoassay to measure PAR levels in real-time analysis was critical for identifying dose levels and time points anticipated to show biochemical effects in human tumors. Equally important were the development and validation of tissue handling procedures that could be used clinically with biopsy specimens to stabilize the pharmacodynamic endpoint. Biopsy procedures used in early clinical trial assessments were "reverse translated" into the animal models as closely as possible. This step allowed proof of feasibility for using the validated assay to assess pharmacodynamic response in needle biopsy samples before entering the clinic. Furthermore, biopsy of live animals under anesthesia replaced the traditional use of necropsy tissue from dying or dead animals to assess dynamic, drug-induced molecular target responses that often use energy-dependent substances like ATP or NAD+.

Despite these improvements in preclinical modeling, it was not feasible to model the phase 0 clinical trial in the mouse with complete accuracy. For example, using general isoflurane inhalation anesthesia in the mice is quite different from using local lidocaine anesthesia for percutaneous biopsy procedures, especially because the variable use of epinephrine in the lidocaine by interventional radiologists could influence PAR levels in the tumor biopsies (19). Furthermore, excisional

Fig. 4. Intertumor and intratumor variability of PAR levels in vehicle- and ABT-888-treated Colo829 xenografts. PAR levels were measured 4 h following drug administration by combined analysis of 1 to 2 quadrants cut from each resected tumor. ABT-888 was administered at doses of 3 or 12.5 mg/kg as indicated (n = 6 animals/group).

A, correlation of PAR levels between small and large tumors following ABT-888 dosing in mice bearing Colo829 xenografts. Large and small tumors occurred randomly on the right or left flank; thus, xenograft size was randomized. The difference in scale of PAR values in vehicle compared with ABT-888 treatment groups was due to significant drug suppression of PAR. B, correlation of PAR levels between first and second quadrants dissected from resected large tumors (n = 6 animals per group). C, correlation of PAR levels between first and second quadrants dissected from resected small tumors (n = 6 animals per group). Values were reported as pg PAR/mL normalized to 100 μg protein. Solid diamond, measured point; line, linear regression fit.

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biopsy procedures are conducted more quickly in mice than in the clinical setting, and the effect of the elapsed time after initial tissue trauma and possibly hypoxia on PAR levels is not well understood.

In conclusion, combining the use of clinical tissue-acquisition procedures with validated pharmacodynamic assays and clinically relevant SOPs for specimen handling is expected to lead to more accurate preclinical modeling. These factors should be carefully considered for future trials of novel, molecularly targeted anticancer therapies. Strict assay performance requirements are justified if the pharmacodynamic endpoint serves as the primary objective in a phase 0 clinical trial.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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