Molecular Imaging Reveals a Role for AKT in Resistance to Cisplatin for Ovarian Endometrioid Adenocarcinoma

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Abstract

Purpose: Ovarian cancer is the fifth leading cause of cancer-related deaths among American women. Platinum-based chemotherapy, such as cisplatin, represents the standard-of-care for ovarian cancer. However, toxicity and acquired resistance to cisplatin have proven challenging in the treatment of patients with ovarian cancer.

Experimental Design: Using a genetically engineered mouse model of ovarian endometrioid adenocarcinoma (OEA) in combination with molecular-imaging technologies, we studied the activation of the AKT serine/threonine kinase in response to long-term cisplatin therapy.

Results: Treatment of cells in culture and tumor-bearing animals with cisplatin resulted in activation of AKT, a key mediator of cell survival. On the basis of these results, we investigated the therapeutic use of AKT inhibition in combination with cisplatin, which resulted in enhanced and prolonged induction of apoptosis and in significantly improved tumor control as compared with either agent alone.

Conclusion: These results provide an impetus for clinical trials using combination therapy. To facilitate these trials, we also show the use of diffusion-weighted MRI as an imaging biomarker for evaluation of therapeutic efficacy in OEA. Clin Cancer Res; 19(1); 158–69. ©2012 AACR.

Introduction

Among American women, ovarian cancer remains the fifth leading cause of cancer-related deaths with an estimated 22,280 new cases for the year 2012 (1). At diagnosis, nearly two thirds of women with ovarian cancer present with advanced stage disease, and their overall 5-year survival is only 27% (2, 3). The vast majority of ovarian cancers are epithelial (carcinomas) and can be classified into 4 major subtypes, including serous, endometrioid, clear cell, and mucinous carcinomas (4). Recent efforts to better understand the genetic differences between these subtypes have shown that mutations predicted to dysregulate key signaling pathways characterize each subtype (5). For example, mutations of genes in the Wnt/β-catenin and PI3K/Pten signaling pathways cooccur in a substantial fraction of ovarian endometrioid adenocarcinomas (OEA; ref. 6). Although genetic differences in the subtypes of ovarian cancer have been recognized, surgical debulking followed by chemotherapy with taxanes and platinum-based drugs remains the first-line therapy for all subtypes (7). Unfortunately, even though most patients initially respond to treatment, tumors eventually relapse due to acquired drug resistance (8, 9). To overcome these hurdles, dose-escalation studies have been explored but have been found intolerable due to toxicity and serious side effects (10). Therefore, a better understanding of the mechanisms leading to drug resistance is urgently needed for the development of novel-treatment paradigms to improve length and quality of life for patients with ovarian cancer.

The cisplatin-resistant phenotype of cancer cells may be due to a number of mechanisms, including alterations that affect the intracellular uptake of cisplatin or altered signaling pathways that ultimately impact the execution of the apoptotic program (10). The PI3K/AKT signaling pathway is important for cell survival, and plays a critical role in a number of other tumor-associated cellular processes, including cell growth, and cell-cycle progression (11). Moreover, a recent study in cultured cells suggested that chemoresistance is mediated by AKT activation through DNA-dependent protein kinase (DNA-PK; ref. 12). However, limited work has been done to study the molecular basis of chemoresistance in a clinically relevant mouse model of ovarian cancer. We have previously described a genetically engineered mouse (GEM) model for OEA, which recapitulates the human disease more closely than traditionally used tumor xenograft models. In this model, simultaneous activation of canonical Wnt/β-catenin and PI3K/AKT signaling invariably leads to ovarian tumor development and is achieved by conditionally inactivating the Apc
**Translational Relevance**

Because many patients with ovarian cancer ultimately relapse after treatment, understanding the mechanisms by which tumor cells acquire resistance to chemotherapy is critically important and should aid in the development of novel and more effective treatment paradigms. In the present study, we used molecular imaging and a genetically engineered mouse ovarian cancer model to show that prolonged administration of cisplatin results in activation of the PI3K/AKT cell survival signaling cascade, which in turn contributes to the therapeutic resistance of tumors. The efficacy of cisplatin was enhanced when combined with an inhibitor of the PI3K/AKT signaling pathway, compared with either agent alone. These results provide a compelling case for including PI3K/AKT signaling pathway inhibitors with cisplatin for treating ovarian cancers. We also show the use of an MRI-based predictive biomarker to guide clinical translation.

**Materials and Methods**

**Cell culture**

Murine OEA-derived tumor cell lines were established by mechanically dispersing ovarian tumor tissues with sterile scalpels followed by digestion at 37°C with 0.05% trypsin–EDTA for 20 minutes. Cells were cultured for 5 passages in Dulbecco’s modified Eagle’s medium (DMEM) containing 10% FBS/1% penicillin/streptomycin (P/S)/1% insulin (Gibco) supplemented with 10% FBS (Gibco). W25 cells display epithelial (cobblestone) morphology by light microscopy and express epithelial markers cytokeratin 8 and 19 by immunofluorescence (13). Simultaneously, we here describe a new cisplatin treatment contributes to resistance to cisplatin-PI3K/AKT cell survival signaling pathway in response to activity (16) and caspase-3 proteolysis (17), we provide and tumor regression in a noninvasive and dynamic manner (14, 15). Using a bioluminescence reporter for AKT activity (16) and caspase-3 proteolysis (17), we provide evidence in the mouse model that the activation of the PI3K/AKT cell survival signaling pathway in response to cisplatin treatment contributes to resistance to cisplatin-induced apoptosis. Simultaneously, we here describe a new modification of our GEM model for OEA, wherein tumor specific caspase-3-dependent apoptosis can be imaged over time in response to therapeutic intervention. We provide validation studies for the use of diffusion-weighted MRI (DW-MRI) as an imaging surrogate for treatment efficacy and identified cisplatin in combination with perifosine as a therapeutic paradigm for future clinical trials.

**Mouse strains**

\( Ap^{loxp}\text{loxP};Pten^{loxP}\text{loxP} \) mice have been previously described in detail (6). The transgenic bioluminescence-apoptosis reporter (Apoptosis reporter\(_{tdTomato}\)) mouse was generated by the transgenic core of the University of Michigan (Ann Arbor, MI). In brief, the elongation factor-1 (EF-1) promoter, which is widely and constitutively expressed, drives the transcription of the tdTomato coding sequence (a derivative of red fluorescent protein). The presence of a transcription stop site and poly-adenylation target site (pA) at the end of the tdTomato coding sequence results in deletion of transcription such that only the tdTomato protein is expressed. In the presence of Cre recombinase, recombination of the loxP sequences results in deletion of the tdTomato coding sequence as well as the adjoining pA sequences. Cre recombinase of the transgene results in transcription of the molecular-imaging reporter as well as an internal ribosome entry site (IRES) and the renilla luciferase (rluc) coding sequence. A single mRNA from the transgene will express the reporter protein (apoptosis reporter) as well as the rLuc protein.

\( Ap^{loxp}\text{loxP};Pten^{loxP}\text{loxP};\text{Apoptosis reporter}^{\text{tdTomato}} \) mice were generated by cross-breeding \( Ap^{loxp}\text{loxP};Pten^{loxP}\text{loxP} \) with \( \text{Apoptosis reporter}^{\text{tdTomato}} \) mice. All the animal experiments were done in accordance with protocols approved by University Committee on Use and Care of Animals of the University of Michigan (IUCJA protocol numbers 08669 and 09921).

**Genotyping**

Animals were genotyped using tail DNA. Genotyping primers used in this study are listed here: Pten\(_{loxP}\text{loxP}\text{loxP}\) allele: forward primer 5’-CTTCCTTCACTTCCATTTCC-3’ and reverse primer 5’-ACTCCCCAAATGAAAC-3’ (18); Ap\(_{loxP}\text{loxP}\text{loxP}\) allele: forward primer 5’-GTCTGTATCATG-CAAAACGCTTTTGAGGGTTGATTC-3’ and reverse primer 5’-CAGCTCGAAGTGTTG-3’ (19); Apoptosis reporter\(_{tdTomato}\) allele: forward primer 5’-GGAATAGACGCA-GAGACGCCAAAAACACATCA-3’ and reverse primer 5’-CTAGAAATAGATCTCCCTCCTCCATCGACTTC-3’.
Western blot analysis

Cells were washed with PBS and lysed with NP-40 lysis buffer (1% NP40, 150 mmol/L NaCl and 25 mmol/L Tris, pH 8.0) supplemented with protease inhibitors (Complete Protease Inhibitor Cocktail, Roche) and phosphatase inhibitors (PhosSTOP, Roche). Tumor tissues were collected at indicated time points, snap-frozen in liquid nitrogen, and stored at −80°C. Tissues were then homogenized in NP-40 lysis buffer supplemented with protease inhibitors and phosphatase inhibitors. Concentration of protein was determined using Lowry assays (Bio-Rad). Equal amount of protein was loaded in each lane and resolved by 4% to 12% gradient Bis-Tris gel (Invitrogen). Proteins were transferred to 0.2-μm nitrocellulose membrane (Invitrogen). Membranes were incubated overnight at 4°C with primary antibodies after blocking, followed by incubation with appropriate horseradish peroxidase (HRP)-conjugated secondary antibody at room temperature for 1 hour. ECL-Plus was used to detect the activity of peroxidase according to the manufacturer's protocol (Amer sham Pharmacia). Antibodies raised against PARP, pAKT (Serine473 and Thr308), total AKT, pH2A.X(Ser139), and total H2A.X were purchased from Cell Signaling Technology according to the manufacturer’s protocol (Amer sham Pharmacia). Antibodies raised against PARP, pAKT (Serine473 and Thr308), total AKT, pH2A.X(Ser139), and total H2A.X were purchased from Cell Signaling Technology (Serine473 and Thr308), total AKT, pH2A.X(Ser139), and total H2A.X were purchased from Cell Signaling Technology.

Immunohistochemistry

After drug treatment, all mice were euthanized and tumor tissues were collected, fixed in 10% (v/v) buffered formalin, and embedded in paraffin. Immunohistochemical staining for Ki67 was completed by the Tissue Core of the University of Michigan Comprehensive Cancer Center using standard techniques. Images from 2 representative ×600 fields in the most cellular areas of tumors were acquired by Olympus BX-51 upright light microscope and an Olympus DP-70 high-resolution digital camera (Olympus Corporation of the Americas). Ki67-positive cells and -negative cells were counted by ImageJ software (Wayne Rasband, NIH).

Bioluminescence imaging of cell culture

Cells were seeded at 5,000 cells per well in a 96-well dish. Twenty-four hours postseeding, cells were incubated with indicated drugs for 20 hours before adding luciferin to a final concentration of 100 μg/mL. Luminescence was recorded by a luminometer (EnVision Xcite Multilabel Reader, PerkinElmer).

PI exclusion assay

Cell viability was determined by propidium iodide (PI) exclusion assay. PI was purchased from Invitrogen. Cells were seeded at 1 × 10^5 cells/mL. Twenty-four hours postseeding, cells were incubated with indicated drugs for 48 hours before trypsinization and subsequently collected by centrifugation (400 × g for 3 minutes). PI staining solution was added at a final concentration of 0.1 μg/mL. Percentage of PI-positive cells was determined and recorded by BD FACSCanto Flow cytometry (BD Biosciences).

Allograft implantation

Six-week-old athymic female mice (CD-1 nu/nu, Charles River Laboratory) were inoculated s.c. with 1 × 10^7 W25 cells expressing the bioluminescence reporters (apoptosis or Akt) into the flank on each side. Injections were a total volume of 200 μL cell suspension in 50% DMEM mixed with 50% BMAT (Becton, Dickinson and Company). Caliper measurements were conducted weekly to determine tumor volumes using the formula V = (length/2) × (width^2) until s.c. tumors reached an approximate volume of 200 mm^3 at which time each animal was randomized into 1 of 4 treatment groups.

Intrabursal injection

Replication-incompetent recombinant adenovirus expressing Cre recombinase (AdCre) under the control of the cytomegalovirus (CMV) promoter (20) was obtained from the University of Michigan’s Vector Core. A total of 5 × 10^7 plaque-forming units (pfu) of AdCre were injected into a total volume of 5 μL containing 0.1% Evans blue (Sigma-Aldrich Inc.) into the right ovarian bursal cavity of 8- to 10-week-old female AploxP/loxP;PtenloxP/loxP;Apoptosis reporter+/− mice. Intrabursal injection was conducted as previously described (21, 22). Each mouse’s left ovarian bursa was untreated, thereby serving as control.

Drug administration

Control and perifosine-treated animals received vehicle or 10 mg/kg perifosine by intraperitoneal injection (i.p.), respectively, 5 times a week for 2 weeks with 2 days off in between treatment weeks. Animals in the cisplatin group received 2.5 or 5 mg/kg cisplatin by i.p. injection 2 times a week for 2 weeks. For combination groups, mice were treated with 2.5 or 5 mg/kg cisplatin 2 times a week with coadministration of 10 mg/kg perifosine.

In vivo bioluminescence imaging

In vivo bioluminescence imaging was carried out by injecting tumor-bearing nude and GEM intraperitoneally with 150 or 300 mg/kg, respectively, of α-luciferin (Biosynth)/PBS solution, respectively, using an IVIS imaging system (PerkinElmer). Postinjection mice were anesthetized with a 1% to 2% isoflurane/air mixture and serial images were acquired over 20 to 30 minutes to capture the peak photon emission for each animal. Regions of interest were drawn around the area of interest in each mouse and peak luminescence values of each series were used for analysis.

MR imaging

MRI on OEA mice was carried out on a 7T Agilent, Inc. Direct Drive system with a quadrature mouse body volume coil (m2m Imaging Corp.). During all MRI procedures, animals were anesthetized with a 1% to 2% isoflurane/air mixture while maintaining body temperature using a heated air system (Air-Therm Heater, World Precision Instruments). Anatomic magnetic resonance images were acquired by a fast spin-echo sequence with the following parameters: repetition time/echo time (TR/TE) = 4,000/15.
millisecond, field of view (FOV) = 40 × 30, matrix size = 128 × 128, slice thickness = 0.5 mm, echo train = 8, echo spacing = 15 milliseconds, and number of slices: 25 to 30. OEA mice were screened for tumor burden once per week from the fourth week after intrabursal surgery. Mice were randomized into vehicle, cisplatin, perifosine, or cisplatin plus perifosine group when their orthotopic tumor sizes reached approximately 50 mm³. Mice were imaged by MRI twice weekly to follow tumor sizes during treatment.

DW-MRI images were obtained from a diffusion-weighted spin-echo sequence, with the following parameters: TR/TE = 2,000/32 milliseconds, FOV = 30 × 30, matrix size = 128 × 64, slice thickness = 1.0 mm, 10 slices, 2 averages, b values (diffusion weighting) of 128 and 795 s/mm². Respiratory gating was conducted using a monitoring system (Small Animal Instruments, Inc., Stony Brook, NY) to eliminate motion artifacts from breathing. DW-MRI scans were conducted before treatment and seven days posttreatment initiation.

**Image reconstruction and analysis**

Volumes of interests (VOI) were manually contoured around the enhancing rim of the tumors on the anatomic images for measurements of tumor volume. To determine the whole-tumor means of apparent diffusion coefficient (ADC), VOIs were manually contoured around the enhancing rim of the tumors on diffusion-weighted image slices at b = 128 s/mm². ADC maps were calculated from the 2 diffusion weightings (b values) using the following equation:

\[
ADC = \frac{\ln(S_1/S_2)}{(b_2 - b_1)}
\]

where \(S_1 \) and \(S_2 \) are the signal intensities at \(b \) values \(b_1 \) and \(b_2 \), respectively. Voxels that exhibited insufficient signal, defined as less than 10 × noise, in the low b value image (\(b = 128 \) s/mm²) were excluded from the analysis. Subsequently, mean ADC values were calculated over the entire tumor volume. All image reconstruction and digital image analysis was accomplished using programs developed in Matlab (The Mathworks).

**Results**

**Resistance to apoptosis in response to cisplatin is reversed by AKT inhibition**

To study the mechanistic basis of cisplatin chemoresistance, we established a primary ovarian tumor cell line (W25) derived from our previously described murine OEA model (13). To enable imaging of caspase-3 activation, a surrogate for apoptosis, we generated a stable cell line (W25-Apop) expressing a previously described bioluminescent apoptosis reporter (17) as illustrated in Fig. 1A.

The induction of apoptosis was evaluated using cultured cells in response to cisplatin alone (20 μmol/L) or in combination with perifosine (30 μmol/L), a small-molecule inhibitor of AKT activity (23). As depicted in Fig. 1B, combination therapy resulted in significantly elevated caspase-3 activation when compared with single agent as measured by an increase in bioluminescence signal. This finding was consistent with conventional Western blot analysis for caspase-3 activity as measured by cleavage of PARP, which was only observed in response to combination therapy (Fig. 1C). In addition, we evaluated overall cell viability using PI exclusion assays (Fig. 1D), wherein the combination therapy showed higher percentage of PI-positivity compared with either agent alone.

To extend these studies in vivo, initial studies focused on following the treatment effects of subcutaneous W25-Apop tumors growing in athymic nude mice. Animals treated with vehicle, perifosine (10 mg/kg, 5 times a week), cisplatin (5 mg/kg, 2 times a week), or combination treatment of cisplatin (5 mg/kg, 2 times a week) and perifosine (10 mg/kg, 5 times a week) were studied using the bioluminescence molecular reporters. The greatest induction of apoptosis as measured by bioluminescence was observed in the cohort of animals treated with the combination of cisplatin and perifosine (Fig. 2A and B). Treatment of tumor-bearing animals with perifosine resulted in enhanced bioluminescence signals (5-fold) on each day of treatment during the first week over the control group. Perifosine as a single agent failed to induce apoptosis during the second week (days 8–12). The combination of cisplatin and perifosine induced apoptosis to a similar extent as perifosine alone in the first week of treatment (5- to 6-fold) but a significant increase in apoptosis (10-fold) was observed in the second week of treatment (Fig. 2A). A significant degree of toxicity as measured by loss of weight was observed in mice treated with cisplatin at 5 mg/kg, 2 times a week. To further evaluate the efficacy of cisplatin and perifosine, we used a lower dose of cisplatin (2.5 mg/kg, 2 times a week). At these doses, we observed a similar enhancement of bioluminescence in the combination group, compared with cisplatin alone after the first day of treatment (Fig. 2C). Furthermore, by the end of 2 weeks of treatment both cisplatin and perifosine as single agents showed significantly increased tumor volumes over baseline measurements, whereas the combination treatment prevented tumor growth during the treatment period (Fig. 2D). Cisplatin alone had some antitumor effect, as tumors were smaller in cisplatin-treated mice than in mice treated with vehicle alone over the 2-week treatment period.

**A role for AKT in resistance to cisplatin treatment**

To investigate the regulation of AKT activity in live cells and animals, we used our previously described bioluminescence AKT reporter (BAR, Fig. 3A). The reporter is designed such that increased bioluminescence activity is observed upon inhibition of the AKT-kinase (16). Using BAR-expressing W25 cells (W25-BAR) we evaluated AKT activity in response to cisplatin and/or perifosine. As expected, perifosine treatment resulted in a significant increase of bioluminescence activity due to AKT inhibition. Unexpectedly, the combination of cisplatin and perifosine showed a 6-fold increase of bioluminescence, suggesting that cisplatin treatment elevated AKT kinase activity and that perifosine treatment resulted in a greater decrease in
AKT activity (Fig. 3B). This was confirmed by phospho-AKT Western blot analysis, which showed that both Ser473 and Thr308 phosphorylation was elevated upon cisplatin treatment in W25-BAR cells, whereas perifosine treatment reversed AKT phosphorylation (Fig. 3C). To investigate if this phenomenon was reproducible in tumors, AKT activity in response to therapies was evaluated in W25-BAR allografts. W25-BAR tumor-bearing animals were randomized into 4 groups consisting of control (vehicle), cisplatin (2.5 mg/kg, 2 times a week), perifosine (10 mg/kg, 5 times a week), or combination therapy when tumors reached 200 mm³ in volume. As shown in Fig. 3D, treatment of s.c. tumor-bearing mice with perifosine expectedly resulted in increased bioluminescence during treatment. In accordance with cell culture results, animals treated with the combination of cisplatin and perifosine showed a prolonged and enhanced increase in bioluminescence signal during treatment. In accordance with cell culture results, animals treated with the combination of cisplatin and perifosine showed a prolonged and enhanced increase in bioluminescence signal during the second week of treatment, indicative of enhanced AKT inhibition (and therefore activity). We hypothesized that repetitive cisplatin exposure during the first week of treatment elevated phospho-AKT levels in tumor allografts, thereby allowing for increased bioluminescence signal to be detected because of simultaneous AKT inhibition. To test this hypothesis, tumor samples were collected following the first week (cycle) of therapy. Western blot analysis confirmed that cisplatin treatment resulted in an increase in AKT activation as measured by phospho-AKT. Combination treatment showed decreased levels of phospho-AKT compared with cisplatin alone indicating that perifosine treatment reversed the activation of AKT (Fig. 3E).

Imaging of apoptosis in a GEM model

The tumor microenvironment—including adjacent normal tissue, stromal cells, vasculature, lymph, and immune cells—impacts the response of tumor cells to therapeutic intervention (23, 26). For the purpose of imaging apoptosis noninvasively in an ovarian cancer animal model, we generated a new reporter mouse by pronuclear microinjection of a transgene containing the apoptosis reporter into fertilized eggs obtained from FVB/N females. The schematic diagram shown in Fig. 4A depicts the transgene apoptosis reporter construct. Apoptosis reporter transgenic animals
were crossed with ApcloxP/loxP;PtenloxP/loxP mice to generate ApcloxP/loxP;PtenloxP/loxP;Apoptosis reporter<sup>+</sup> mice for use in subsequent experiments. In this new OEA model with the built-in apoptosis imaging reporter, Cre-expression resulted in the deletion of both copies of Apc and Pten and expression of the apoptosis reporter in transformed ovarian surface epithelial cells. Mice injected with AdCre are referred hereafter as Apc<sup>−/−</sup>;Pten<sup>−/−</sup>;Apoptosis reporter<sup>+</sup>, indicating successful Cre-mediated recombination. Representative images of bioluminescence activity in Apc<sup>−/−</sup>;Pten<sup>−/−</sup>;Apoptosis reporter<sup>+</sup> mice with ovarian tumors before and following 1 day of treatment are shown in Fig. 4B. Bioluminescence signals were only detected in the right abdomen, indicative of tissuespecific activation of the apoptosis reporter upon AdCre injection into the right ovary. Consistent with our previous data obtained in cell culture and allografts, bioluminescence activity increased following combination therapy indicating activation of caspase-3 had occurred. Tumor progression in Apc<sup>−/−</sup>;Pten<sup>−/−</sup>;Apoptosis reporter<sup>+</sup> animals was followed over time using MRI after AdCre injection. Once tumor volumes reached approximately 50 mm<sup>3</sup>, animals were randomized into 4 treatment groups: vehicle, perifosine (10 mg/kg 5 times a week), cisplatin (5 mg/kg 2 times a week), and combination group, which were treated with 5 mg/kg cisplatin 2 times a week and 10 mg/kg perifosine 5 times a week. Arrows indicate days of treatment for cisplatin and perifosine. Bioluminescence signals were normalized to tumor volumes and pretreatment values at each time point. Mean-fold induction is plotted ± SEM. B, representative bioluminescence images pre- and posttreatment of each treatment group are shown. C, bioluminescence imaging of W25-Apop allografts at lower cisplatin doses (2.5 mg/kg) at one time point (6 hours posttreatment). Bioluminescence signals were normalized to pretreatment values at each time point. Mean-fold induction is plotted ± SEM. D, percentage change of tumor volumes 2 weeks posttreatment initiation. Tumor volumes were measured by caliper pre- and posttreatment. Data represent mean ± SEM.

Figure 2. Induction of apoptosis in tumor allograft by combination treatment. A, bioluminescence imaging of W25-Apop allografts. When tumors reached 200 mm<sup>3</sup> or more, animals were randomized into 4 treatment groups: vehicle, perifosine (10 mg/kg 5 times a week), cisplatin (5 mg/kg 2 times a week), and combination group, which were treated with 5 mg/kg cisplatin 2 times a week and 10 mg/kg perifosine 5 times a week. Arrows indicate days of treatment for cisplatin and perifosine. Bioluminescence signals were normalized to tumor volumes and pretreatment values at each time point. Mean-fold induction is plotted ± SEM. B, representative bioluminescence images pre- and posttreatment of each treatment group are shown. C, bioluminescence imaging of W25-Apop allografts at lower cisplatin doses (2.5 mg/kg) at one time point (6 hours posttreatment). Bioluminescence signals were normalized to pretreatment values at each time point. Mean-fold induction is plotted ± SEM. D, percentage change of tumor volumes 2 weeks posttreatment initiation. Tumor volumes were measured by caliper pre- and posttreatment. Data represent mean ± SEM.
indicative of caspase-3–independent cytotoxicity due to the high dose of cisplatin, which was also observed in our allograft study (Fig. 2A). Quantitative analysis of the MRI data show tumor volumes were significantly reduced in the combination treatment over all other treatment groups (Fig. 4E), thus confirming our previous results using the OEA tumor allografts. Target inhibition by drug was confirmed by Western blotting against phospho-AKT(Ser473) and total AKT of tumor tissues obtained from animals treated with perifosine. As depicted in Fig. 4F, perifosine treatment resulted in a decrease in phospho-AKT levels at 3 hours posttreatment initiation.

Figure 3. Increase in AKT reporter activity upon combination treatment. A, schematic of BAR. B, bioluminescence assay in W25-BAR cells after 20 hours treatment with vehicle, cisplatin (40 μmol/L), perifosine (30 μmol/L), or both of perifosine and cisplatin. Fold induction of bioluminescence signals in each group was calculated at indicated time points by normalizing bioluminescence signals to the values of vehicle group. Three independent experiments were carried out and mean ± SEM is depicted. C, representative Western blot analysis of W25 cell lysates from vehicle-, cisplatin (40 μmol/L)-, perifosine (30 μmol/L)-, or both treated cells. Antibodies against pAKT Ser473, pAKT Thr308, and total AKT were used. D, bioluminescence imaging of W25-BAR reporter allografts. When tumors reached 200 mm3 or more, animals were randomized into 4 treatment groups: vehicle, perifosine (10 mg/kg 5 times a week), cisplatin (2.5 mg/kg 2 times a week), and combination group, which are treated with 2.5 mg/kg cisplatin 2 times a week and 10 mg/kg perifosine 5 times a week. Arrows indicate days of treatment for cisplatin and perifosine. Bioluminescence signals were normalized to tumor volumes and pretreatment values at indicated time points. Mean-fold induction is plotted ± SEM. E, representative images of Western blot analysis of tumor tissue derived from OEA transgenic at one week after cisplatin treatment. Antibodies against pAKT Ser473, pAKT Thr308, and total AKT were used. F, representative images of Western blot analysis from W25 cells treated with vehicle, cisplatin (40 μmol/L), perifosine (30 μmol/L), or both. pH2A.X Ser139 and total H2AX were detected by specific antibodies.

DW-MRI can be used to measure changes in cellular density within tumor tissue and has been established as a clinically relevant surrogate imaging biomarker for treatment response assessment in patients with cancer (27, 28). We conducted DW-MRI on tumor-bearing mice to evaluate the effects the treatment as well as the ability of DW-MRI to detect and differentiate the effectiveness of each treatment. As shown in Fig. 5A and B, we observed a decrease in ADC values in vehicle and perifosine-treated animals after 2 weeks of treatment suggesting that perifosine alone is not efficacious in inducing cell death. The observed decrease in ADC values in vehicle and perifosine groups suggested that
cells were undergoing active proliferation resulting in increased tumor cellularity over this time period. This finding was further supported by immunohistochemical analysis of tumors obtained from these animals 1 week after treatment initiation. Ki67 staining, indicative of cell proliferation, increased in vehicle and perifosine-treated animals as shown in Fig. 5C and D. However, cisplatin- and combination-treated animals showed increased ADC values (Fig. 5A and B) and decreased Ki67 staining (Fig. 5D), which suggested that increased cell death was the likely cause of the resultant tumor regression as shown in Fig. 4E.

In summary, these studies revealed that combination treatment of cisplatin and perifosine was more efficacious than either drug alone in inducing apoptosis, and thereby tumor regression, by using our new reporter mouse model of OEA in conjunction with noninvasive imaging modalities.

Discussion

Patients with ovarian cancer treated with the chemotherapeutic agent, cisplatin, usually show an initial response, yet ultimately succumb to their disease due to the development of resistance (10). Regulation of cellular-drug uptake, increased DNA damage repair, and inhibition of apoptosis have been proposed to cause cisplatin resistance (29). The development of strategies for chemosensitization and prevention of therapeutic resistance remains a major goal with important clinical implications. Although a large body of work has been conducted toward this aim, the model systems typically use cultured cells and/or immunocompromised...
mice bearing subcutaneous xenografts. In addition, analyses of molecular events in these model systems involves resection of tumor cells for \textit{ex vivo} assays and thus provide only a nonquantitative snapshot of a dynamically changing and highly interactive cascade of signaling events following therapeutic intervention. The present study uses recent advances in GEM ovarian cancer models as well as the development of molecular-imaging biomarkers, which enable quantitative, noninvasive, and temporal imaging of dynamic molecular events in living animals. Combining our tumor model systems with anatomic and molecular-imaging approaches provided an opportunity to gain novel insights into the roles of PI3K/AKT signaling and the apoptotic machinery in the development of therapeutic resistance to cisplatin.

Our initial study used a mouse OEA cell line derived from an ovarian tumor, which was engineered to express the apoptosis reporter. This line was subcutaneously implanted allowing for detection of caspase-3 activation in perifosine-treated animals using bioluminescence imaging. While the imaging signal increased during the first week, a significant decline was observed during the second week of treatment. We reasoned that the cells’ dependency on the PI3K/AKT pathway leads to an initial induction of apoptosis upon inhibition of AKT activity by perifosine, which may later be compensated by activation of alternate survival signaling pathways. In support, we and others have previously reported that AKT inhibition results in activation of compensatory signaling through MEK/ERK or other signaling pathways (13, 30). This finding may provide additional rationale for the simultaneous targeting of PI3K/AKT and MEK/ERK signaling pathways, but remains to be investigated for the treatment of OEA. Intriguingly, the caspase-3 reporter allowed us to determine that cell death and tumor regression induced by cisplatin in cell culture and in allografted or transgenic animals, respectively seemed to be largely caspase-3 independent. This is not surprising as cisplatin has been shown to exert its effects by inducing DNA damage, cell-cycle arrest and ultimately necrotic cell death (31, 32), which serves to further validate the use of these molecular-imaging reporters in the context of preclinical drug optimization studies.

Initial response to platinum-based therapies in the treatment of patients afflicted with ovarian cancer is usually high, yet most patients relapse due to acquired resistance. Recent studies by Stronach and colleagues comparing cisplatin-resistant and cisplatin-sensitive cell lines revealed a
significant increase in phosphorylated AKT upon cisplatin treatment. AKT inhibition sensitized resistant cells to cisplatin, whereas inhibition of AKT in cisplatin-sensitive lines had little effect on caspase-3/7 induction (12). With the ability to image and thus quantify AKT and caspase-3 activity in live tumor-bearing animals dynamically over time, our results support the concept that activation of AKT contributes to cisplatin resistance and likely results from prior exposure to the agent.

Activation of AKT is regulated by various factors, including insulin and the DNA damage response. Several reports have thus far shown that AKT’s complete activation depends on its phosphorylation at Ser473 and Thr308. Interestingly, Thr308 is phosphorylated by 3-phosphoinositide-depend-ent kinase 1 (PDK1; ref. 33), whereas Ser473 is likely regulated by mTORC2 (34), DNA-PK (35), and ATM (36). Here, we present data indicating that cisplatin alone or in combination with perifosine induced similar DNA damage, yet single-agent treatment with cisplatin induced AKT activation and resistance to apoptosis. These findings suggest that AKT activation by cisplatin may be mediated by the DNA damage response. Supporting these findings are the results of a recent study, which showed DNA-PK-dependent regulation of AKT phosphorylation upon cisplatin treatment (12). However, as ATM is also activated following DNA double-strand breaks and has been implicated in radiation-induced AKT activation (24), the possibility remains that ATM may also play a role in regulating AKT phosphorylation, which should be the subject of further investigations.

The PI3K/AKT pathway plays an important role in the cell survival pathway. The enhanced effect that we observed following cisplatin and perifosine treatments, suggests that cisplatin activates the PI3K/AKT pathway thereby preventing apoptosis. Simultaneous inhibition of AKT activity by perifosine treatment can overcome this effect resulting in apoptosis. In fact, previous studies have shown that AKT through the modulation of p53 activity as well as activation of various apoptotic factors can lead to resistance to apoptosis (37–39).

Genetically engineered OEA mouse models closely recapitulate the human disease, thereby providing an excellent opportunity to study this subtype of ovarian cancer and optimize therapeutic paradigms for future clinical investigation (13). We have recently shown that the OEAs arising in our model system are inhibited by the mTOR inhibitor rapamycin, 2 mechanistically distinct AKT inhibitors (perifosine and API-2), as well as cisplatin plus paclitaxel (13), but combinations of conventional with targeted therapies have not been evaluated in our model system until now. Although we have not yet tested effects of cisplatin and perifosine in GEM models of serous carcinoma, we note that a substantial fraction of high-grade serous carcinomas also have activated PI3K/AKT signaling, often on the basis of amplification PIK3CA, AKT1, or AKT2 (3). Hence, our finding that cisplatin plus perifosine is more effective than either agent alone, may apply to other ovarian cancer subtypes besides the subset of endometrioid carcinomas with activated PI3K/AKT signaling. We also note that other chemotherapeutic agents used to treat ovarian cancers, including paclitaxel, have also been shown to activate PI3K/AKT signaling (40). In addition, inhibition of phosphoinositide 3-kinase (PI3K) has been shown to increase efficacy of paclitaxel in ovarian cancer model systems (41). Even more recently, perifosine plus docetaxel were used to treat patients with platinum- and taxane-resistant or refractory ovarian carcinomas in a phase 1 clinical trial (42). Interestingly, all 4 (of 21) patients who achieved partial remission or stable disease had either endometrioid or clear cell carcinomas, and 2 had mutations predicted to activate PI3K/AKT signaling. Clearly, more work is required to determine whether activation of AKT by cisplatin or paclitaxel is a drug-specific or more general effect, and to define the tumor subsets most likely to respond to therapeutic regimens including PI3K/AKT pathway inhibitors.

Monitoring tumor progression and molecular events in intra-abdominal tumors usually involves sacrificing large number of animals for traditional biochemical assays. To enable the detection of molecular events within tumors longitudinally, we used our previously developed bioluminescence reporters along with anatomical imaging and DW-MRI. The use of the bioluminescence reporters provided for the ability to quantify the extent of apoptosis and AKT activation over time. We have shown in vivo that repeated cycles of cisplatin treatment resulted in AKT activation, thus revealing molecular mechanisms that contribute to the development of cisplatin resistance. The combination of cisplatin and perifosine was able to inhibit AKT activity and overcome resistance to cisplatin through apoptotic induction and therefore may present a more effective therapeutic paradigm for the treatment of patients with ovarian cancer.

Although bioluminescence imaging represents a vital tool for imaging molecular events in animal models, it has its limitations in the clinical settings. To develop an imaging biomarker that can be clinically translated for use in patients with ovarian cancer, we evaluated the application of DW-MRI as a surrogate for detection of treatment associated loss of tumor cellularity. DW-MRI has shown promise as a surrogate biomarker of therapeutic response with correlations to survival outcomes in patients with cancer (27, 43, 44). In our study, DW-MRI revealed that both high doses of cisplatin and in combination with perifosine, significant loss of tumor cellularity occurs in contrast to treatment using perifosine alone, which was found to have a minimal effect on reducing tumor cell density.

In summary, animal models with defined mutations in key signaling pathways are powerful tools to provide a better understanding of therapeutic efficacy of single agents and to explore the efficacy of combination therapeutic strategies. Molecular-imaging technologies such as bioluminescence imaging of mouse models as well as MRI in preclinical and clinical studies not only provide an accurate and noninvasive measure of tumor burden and efficacy, but can also enable validation of drug target interactions and...
acquired drug resistance. Results described here provide an impetus for initiation of clinical studies with integrated DW-MRI biomarker readouts to evaluate pharmacologic inhibition of the PI3K/AKT survival signaling pathway when combined with cisplatin to prevent the development of therapeutic resistance and thus significantly impact overall survival in women with OEA.

Disclosure of Potential Conflicts of Interest

B.D. Ross is employed as Founder by Imbio, LLC and has ownership interest (including patents) in Imbio, LLC. A. Rehemtulla has ownership interest (including patents) in Imbio, LLC. No potential conflicts of interest were disclosed by the other authors.

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Analysis and interpretation of data (e.g., statistical analysis, bioinformatics, computational analysis): H. Wang, S. Galbán, C.J. Galbán, A. Rehemtulla

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