Vascular Disruption in Combination with mTOR Inhibition in Renal Cell Carcinoma

Leigh Ellis1, Preeti Shah4, Hans Hammers4, Kristin Lehet1, Paula Sotomayor1, Gissou Azabdaftari2, Mukund Seshadri3, and Roberto Pili1

Abstract

Renal cell carcinoma (RCC) is an angiogenesis-dependent and hypoxia-driven malignancy. As a result, there has been an increased interest in the use of antiangiogenic agents for the management of RCC in patients. However, the activity of tumor-vascular disrupting agents (tumor-VDA) has not been extensively examined against RCC. In this study, we investigated the therapeutic efficacy of the tumor-VDA ASA404 (DMXAA, 5,6-dimethylxanthenone-4-acetic acid, or vadimezan) in combination with the mTOR inhibitor everolimus (RAD001) against RCC. In vitro studies were carried out using human umbilical vein endothelial cells and in vivo studies using orthotopic RENCA tumors and immunohistochemical patient tumor-derived RCC xenografts. MRI was used to characterize the vascular response of orthotopic RENCA tumors and immunohistochemical patient tumor-derived RCC xenografts to combination treatment. Therapeutic efficacy was determined by tumor growth measurements and histopathologic evaluation. ASA404/everolimus combination resulted in enhanced inhibition of endothelial cell sprouting in the 3-dimensional spheroid assay. MRI of orthotopic RENCA xenografts revealed an early increase in permeability 4 hours posttreatment with ASA404, but not with everolimus. Twenty-four hours after treatment, a significant reduction in blood volume was observed with combination treatment. Correlative CD31/NG2 staining of tumor sections confirmed marked vascular damage following combination therapy. Histologic sections showed extensive necrosis and a reduction in the viable rim following combination treatment compared with VDA treatment alone. These results show the potential of combining tumor-VDAs with mTOR inhibitors in RCC. Further investigation into this novel combination strategy is warranted.

Introduction

Renal cell carcinoma (RCC) is a lethal genitourinary malignancy that accounts for 85% of primary renal neoplasms (1). In 2010, 58,240 patients were diagnosed with RCC in the United States, with 13,040 reported cancer-related deaths (2). Improved understanding of the biology of RCCs over the last decade has resulted in increased investigation into the use of targeted therapeutics for RCC. Primary and metastatic RCCs are angiogenesis-dependent and hypoxia-driven malignancies (3, 4). As a result, several agents targeting tumor angiogenesis are being actively investigated against RCC in preclinical and clinical studies (4, 5). These include inhibitors of the mTOR and VEGF pathways. Targeted agents that have recently received approval by the Food and Drug Administration for clinical use include the mTOR inhibitors, everolimus and temsirolimus, and the receptor tyrosine kinase inhibitors (TKI), sorafenib and sunitinib. Although TKI and mTOR inhibitors have shown clinical benefit in RCC, patients with advanced disease fail these targeted therapies and develop refractory disease. Therefore, investigation into novel combination treatment approaches to improve clinical outcome remains a high priority.

The significance of the mTOR signaling pathway in RCC is well recognized (6). Pharmacologic inhibition of mTOR has been shown to inhibit tumor growth in preclinical models and in patients with RCC (6–8). In addition to their direct antitumor effects, mTOR inhibitors have been shown to exhibit also significant antiangiogenic activity (9, 10). Rapamycin and its analogues have a direct inhibitory effect of endothelial cell proliferation. mTOR pathway inhibition also impairs protein synthesis of angiogenesis-related factors including HIF (11).

Tumor vascular disrupting agents (tumor-VDA) constitute a unique class of drugs that are being considered as...
a valid therapeutic strategy for clinical development (12). Tumor-VDAs target established tumor vasculature, which is required by the tumor to survive and grow (12, 13). This action is distinct from that of antiangiogenic agents, which predominantly target neovascularization (12–14). One such tumor-VDA is the small molecule ASA404 (vadimezan, 5,6-dimethylxanthenone-4-acetic acid; DMXAA), that has been shown to exhibit potent antitumor activity in combination with chemotherapy in preclinical models (15, 16). ASA404 induces apoptosis of tumor vascular endothelial cells, cytokine production, and tumor vascular collapse—effects that culminate in tumor necrosis in vivo (17–19).

Because mTOR inhibitors and tumor-VDAs target distinct tumor vascular networks, we investigated the therapeutic potential of ASA404 in combination with the mTOR inhibitor, everolimus (RAD001). It was our hypothesis that combined destruction of established vessels and inhibition of angiogenesis would result in improved anti-tumor activity against RCC. To test this hypothesis, studies were carried out using endothelial cells in vitro and in vivo using 2 different RCC model systems. Experimental studies were carried out in vitro using human umbilical vein endothelial cells (HUVEC) and in vivo using orthotopic RENCA tumors and immunohistochemical patient tumor-derived RCC xenografts. MRI was used to characterize the vascular response of orthotopic RENCA xenografts to combination treatment. Therapeutic efficacy was determined by tumor growth measurements and histopathologic evaluation.

Materials and Methods

Cell culture and reagents

The murine renal cell carcinoma (RENCA) cell line was purchased from the American Type Culture Collection and maintained in RPMI culture media (Life Technologies) supplemented with 10% FBS, 1% pen/strep and incubated at 37°C in 5% CO₂. HUVECs were obtained from Lonza and maintained in EBM2 media (Lonza) with all included growth factors. No further authentication was conducted on these cell lines. ASA404 (Vadimezan, formerly known as DMXAA,) and everolimus were kindly provided by Novartis Institute of Biomedical Research, Basel, Switzerland. The MR contrast agent, albumin-(GdDTPA)₃₅ (provided by the Contrast Media Laboratory, University of California, San Francisco, San Francisco, CA (Drs. Robert Brasch and Yanjun Fu). For in vitro work, everolimus stock was made in dimethyl sulfoxide and aliquoted and stored at −20°C. ASA404 was made fresh on the day of treatment in culture medium. For in vivo experiments ASA404 was administered weekly at 22 mg/kg or 25 mg/kg in 5% sodium bicarbonate solution (from 7.5% stock solution w/v, Invitrogen) by intraperitoneal (i.p.) injection. Everolimus was freshly prepared and administered in vivo by oral gavage in distilled water at 2.5 mg/kg on a 5 days on/2 days off schedule.

Three-dimensional spheroid assay

Tissue culture flasks were coated with 0.5% gelatin in PBS and HUVECs were propagated in EBM2 containing all the growth factors. Hydrated Cytodexin beads were equilibrated with complete EBM2 medium without VEGF and were incubated with HUVECs for 4 hours in a 37°C incubator. Spheroids comprising the beads and HUVECs were embedded in fibrin after activation of fibrinogen in the presence of thrombin in 48-well plates. Endothelial cells were allowed to sprout and form lumen when treatment was started alone or in combination. ASA404 and everolimus were dissolved in EBM2. Following treatment, plates were fixed in formalin and stained with 4',6-diamidino-2-phenylindole (DAPI) in PBS. Pictures were captured on a Nikon E 2000 microscope and quantitation was carried out using Image J software (NIH).

In vivo animal models

The Institute Animal Care and Use Committee at Roswell Park Cancer Institute approved all mouse protocols used in this study. Female 4- to 6-week-old BALB/c mice (National Cancer Institute) were kept in a temperature-controlled room on a 12/12 hours light/dark schedule with food and water ad libitum. Orthotopic implantation of RENCA cells has been previously described (20). Briefly, RENCA cells (5 × 10⁵) harvested from nonconfluent monolayer cell cultures in 50 μL of medium were injected under the renal capsule and tumor uptake and growth was monitored by palpation. The human xenograft model designated immunohistochemistry (21) was also used. Female 4- to 6-week-old athymic nude mice were purchased from the National Cancer Institute (Frederick). Immunohistochemical tumor pieces 3 × 3 × 3 mm were transplanted into a new cohort of mice for expansion and eventual drug studies. Before starting the treatment with either model, tumor-bearing mice were divided into homogenous groups (8–9 per group) according to tumor burden determined by size.

For in vivo studies, tumor-bearing mice were treated with ASA404 (22 mg/kg once weekly; i.p. injection), everolimus (2.5 mg/kg 5 d on 2 d off; oral gavage), or combination for approximately 10 days in the RENCA model and 35 days in the immunohistochemistry model. Mice were monitored for toxicity by weekly body weight measurements and tumor growth was measured twice weekly. Tumor tissue was harvested, weighed, and fixed in 10% normal buffered formalin before being embedded in paraffin. Four (4 μm) samples were stained with hematoxylin and eosin (H&E) for further analysis. Image acquisition was carried out by using a Scanscope XT system (Aperio Imaging) and analyzed using Imagescope software (Aperio).

Bioluminescence imaging

Serial bioluminescence imaging (BLI) was carried out using the Xenogen IVIS in vivo Imaging System (Caliper Life Science). Animals were injected i.p. with D-luciferin potassium salt dissolved in PBS. Ten minutes after
D-luciferin injection, mice were imaged under isoflurane inhalational anesthesia for detection of luciferase activity (20).

MRI

MRI studies were conducted using a 4.7-T/33-cm horizontal bore magnet (GE NMR Instruments) incorporating AVANCE digital electronics (Bruker Biospec, ParaVision; Bruker Medical). Induction of anesthesia before imaging and maintenance of anesthesia during imaging was achieved by inhalation of isoflurane (~2%–3% in oxygen). Anesthetized animals were placed on an acrylic sled equipped with respiratory and temperature sensors and positioned within the magnet. An air heater system was used to maintain animal temperature in conjunction with the sensors embedded within the sled, which provided continuous feedback during imaging.

Preliminary scout images were acquired on the sagittal and axial planes to assist in slice prescription for subsequent scans. Multislice non-contrast-enhanced T2-weighted images were acquired on the coronal and the axial planes with the following parameters: TE/TR = 41/2,500 ms, matrix size 256 × 192, 1 mm thick slices, FOV 3.2 × 3.2 cm, NEX = 4. T1-relaxation rates (R1) were measured using a saturation recovery, fast spin echo sequence before and after administration of the intravascular MR contrast agent, albumin-(GdDTPA)₃₅ (0.05 mmol/kg) as described previously (21). Image processing and analysis were carried out using commercially available software (AnalyzePC; AnalyzeDirect). Raw data were reformatted and object maps of desired regions of interest were outlined. Signal intensities from regions of interest were obtained and mean intensity within the regions of interest was used for calculating the T1 relaxation at each TR time.

The change in relaxation rate (ΔR1) was then calculated for tumor and normalized to the contralateral kidneys. Vascular permeability was calculated by measuring the ΔR1 of tumors in control and treated animals at 4 hours posttreatment. Linear regression analysis of the normalized ΔR1 versus time curve was carried out to compute the fractional blood volume (fBV) of tumors (22, 23). Values obtained at 24 hours were compared with baseline pretreatment estimates. T1 relaxation maps (R1 maps) of animals were calculated on a pixel-by-pixel basis in MATLAB (Math Works, Inc.). For each treatment group, T1 enhancement maps (ΔR1 maps) were generated at baseline (pretreatment) and 24 hours posttreatment by subtracting a postcontrast R1 map from the precontrast R1 map of the same animal.

Immunostaining for NG2 and CD31

Twenty-four hours after treatment, mice were anesthetized with ketamine (100 mg/kg; i.p.) plus xylazine (10 mg/kg; i.p.) and perfused with 1% paraformaldehyde (Sigma-Aldrich) at 2 mL/min using cardiac puncture of the left ventricle. After perfusion with fixative, tissue was dissected and immersed in 1% paraformaldehyde for 2 hours followed by immersion in 30% sucrose (Sigma-Aldrich) for 48 hours and embedded in tissue-freezing media [ornithine carbamy transferase (OCT); Tissue-Tek, Sakura Finetek USA]. OCT blocks were sectioned (6 μm) and slides were immersed in 1% bovine serum albumin (Sigma-Aldrich) in PBS for 30 minutes. Sections were incubated overnight with the primary antibody, anti-NG2 Chondroitin Sulfate Proteoglycan (1/200, AB5320, Millipore) or antiimmunouse CD31 (1/50, 550274, BD Biosciences). Slides were washed with PBS and sections were incubated with the secondary antibody fluorescein isothiocyanate-conjugated antirabbit Ig (1/400, 554020, BD Biosciences) or Cy3-conjugated antiglut IgG (1/400, A10522, Invitrogen). Sections were counterstained with DAPI and mounted with Vectashield (Vector Laboratories). Sections were visualized with a Zeiss Axioskop-2plus microscope (Axioskop, Carl Zeiss). For NG2 and CD31 immunostaining quantification, 2 to 3 pictures of 3 samples per treatments were processed using Image J software to subtract background and to determine the integrated density of pixels. Results were expressed as the average per treatment of integrated density of pixels.

Quantification of tumor necrosis

Slides containing histologic sections of control and treated tumors were scanned and digitized using the Scanscope XT system (Aperio) and images of whole tumor sections were captured using the ImageScope software. Areas of necrosis were manually traced using the medical imaging software, Analyze (AnalyzePC; AnalyzeDirect) and reported as a percentage of the whole tumor area.

Statistical analyses

All measured values are reported as mean ± SE. Values of P < 0.05 were considered statistically significant. The 2-tailed t test was used for comparing the individual treatment groups with the controls or combination treatment with the individual treatment groups at different times. Linear regression analysis of the change in R1 over time curve was carried out to compute differences in fBV of tumors. All statistical calculations and analyses were done using GraphPad Instat (ver. 5.00, GraphPad Software).

Results

Endothelial cell response to everolimus and ASA404 treatment in vitro

The 3-dimensional (3D) spheroid sprouting assay was carried out to investigate the antiangiogenic/antivascular activity toward HUVECs of everolimus and ASA404 (Fig. 1A and B, respectively) individual treatments or in combination. As shown in Fig. 1C (top panel), HUVECs underwent angiogenic-mediated proliferation generating sprouts and formed new vessels in vitro in fibrin gel. After 24 hours of treatment with 100 μmol/L ASA404, 1 nmol/L everolimus or combination, the angiogenic potential of HUVEC spheroids was assessed. ASA404 or everolimus single treatments moderately inhibited HUVEC
sprouting, while ASA404/everolimus combination displayed marked disruption of HUVECs sprouting ability (Fig. 1C). Further assessment by staining HUVEC sprouts in 3D culture with the DNA dye DAPI indicated that ASA404 single treatment did not induce significant loss in viable HUVEC sprouts ($P = 0.08$), whereas significant loss of HUVEC cell viability was found to be mediated by everolimus ($P = 0.03$). ASA404/everolimus combination treatment significantly increased disruption of HUVEC sprouts compared with ASA404 ($*, P = 0.008$) and everolimus ($**, P = 0.01$) single treatments (Fig. 1D).

**Combined mTOR inhibition and VDA treatment of immunohistochemical RCC xenografts**

To investigate the antitumor activity of ASA404 and everolimus in vivo, we treated nude mice-bearing subcutaneous grafted human immunohistochemical renal cell carcinoma xenografts with either everolimus (5 mg/kg; 5 d on 2 d off), ASA404 (25 mg/kg; once a week) or in combination for 35 days. All therapy groups showed minimal toxicities as assessed by body weight (data not shown). Tumor growth calculations and tumor weight measurements were obtained along with histologic evaluation of tumor response to therapy. Figure 2A shows H&E stained tumor sections of control and treated immunochemical xenografts. Tumors treated with ASA404 or everolimus showed moderate increases in amorphous hyaline deposits indicative of cellular necrosis compared with control-treated tumors. In contrast, everolimus/ASA404 combination treatment of immunohistochemical tumors resulted in marked induction of tumor hemorrhaging (He) and hyalinization (Fig. 2A). A marked reduction in tumor weight was seen following combination treatment compared with controls. However, this reduction was not statistically significant compared with either monotherapy (Fig. 2B). Combination treatment resulted in a significant delay in tumor growth compared with single treatments (Fig. 2C; ASA404, $P = 0.03$ and everolimus, $P = 0.05$).

**Bioluminescence and MRI of orthotopic RENCA tumors**

We examined the antivascular and antitumor activity of ASA404/everolimus combination using the orthotopic RENCA tumor model. For these studies, a dual modality imaging-based approach using BLI and MRI was used. Serial BLI was carried out once every 3 to 4 days after orthotopic injection of luciferase-transfected RENCA cells to visualize successful tumor establishment in the kidneys based on bioluminescence signal (photon counts) as shown in Fig. 3A. Approximately, 2 weeks postimplantation, noncontrast-enhanced T2-weighted MRI was carried out to confirm “tumor take” and for assessment of tumor morphology and volume. Animals were then randomized into control or one of the treatment groups. Figure 3A shows bioluminescence and MR images of a control mouse-bearing orthotopic RENCA tumor in the right kidney (outlined in yellow). The left kidney is outlined in red on the MR images. MR images revealed invasive tumor growth that was confirmed by histologic examination (lower right panel).

**Vascular response to combined mTOR inhibition and VDA therapy in vivo**

Contrast enhanced MRI was carried out to characterize the in vivo tumor vascular response of RENCA tumors to mTOR and VDA treatments when given alone and in combination. For these studies, mice with volume-matched tumors were studied ($n = 3$ per group; mean tumor volume $87.12 \pm 15.55$ mm$^3$).

We first examined treatment induced changes in vascular permeability by measuring the change in Ti-relaxation rates ($\Delta R1$) of RENCA tumors and contralateral kidneys (Fig. 3B). Values obtained 4 hours post-ASA404, everolimus, or combination treatment were compared with untreated controls. Consistent with previous observations in subcutaneous tumor models, ASA404 treatment resulted in a significant increase ($P < 0.05$) in vascular permeability evidenced by increased accumulation of $\Delta R1$ ($0.578 \pm 0.08$) compared with controls ($0.307 \pm 0.04$). Although everolimus alone did not result in any change in vascular permeability ($0.379 \pm 0.16$, $P > 0.05$), tumors treated with the combination also showed an increase in $\Delta R1$ ($0.439 \pm 0.04$) compared with controls. However, this difference was not statistically significant (Fig. 3B). No significant difference in contrast agent accumulation was observed in the contralateral kidneys of animals in the control and treatment groups. Figure 3C.
shows axial T2-weighted images and corresponding R1 maps of a representative mouse from each group at 4 hours posttreatment. Increased accumulation of the contrast agent can be visualized on the enlarged ROI of the tumor 4 hours post-ASA404 treatment compared with untreated controls.

We next investigated the effects of ASA404, everolimus, and combination treatment on fBV of RENCA tumors. Figure 4 shows T1-enhancement maps of tumors at baseline (pretreatment) and 24 hours posttreatment for all 3 treatment groups. Corresponding axial T2-weighted images are also shown for visualization of tumor extent (outlined in black). Reduction in contrast enhancement was seen 24 hours following treatment with ASA404 alone (Fig. 4A), everolimus alone (Fig. 4B), and combination (Fig. 4C) compared with baseline postcontrast images. All 3 treatments resulted in a significant reduction in fBV at 24 hours (Fig. 4D). Treatment with ASA404 alone resulted in approximately 50% reduction fBV of RENCA tumors (0.207 ± 0.04; P < 0.0001) compared with pretreatment values (0.395 ± 0.02). Orthotopic RENCA tumors in animals treated with everolimus alone also exhibited a significant reduction in fBV (0.154 ± 0.01; P < 0.001) at the 24-hour time point compared with baseline estimates (0.289 ± 0.02). Combination treatment resulted in a similar reduction in fBV (0.165 ± 0.02; P < 0.0001) at the 24-hour time point compared with baseline measures (0.207 ± 0.04; P < 0.0001).

MRI-based changes in vascular function were correlated with dual immunostaining of tumor sections for the pan endothelial cell adhesion molecule, CD31, and the pericyte marker, NG2. Histologic assessment of tumor sections was also carried out to visualize tumor necrosis following treatment. Consistent with the MRI results, CD31/NG2 staining revealed marked vascular damage following ASA404 alone and combination treatment (Fig. 5A, bottom panel and Fig. 5B and C). A significant reduction (P < 0.05) in CD31 staining was seen following combination treatment compared with everolimus monotherapy, but not control treated animals (P = 0.05). Importantly, immunostaining showed that either drug as single treatment or in combination was tumor specific, as staining of the non-tumor-bearing contralateral kidney displayed no antivasular-mediated effects (Fig. 5A, top panel).
Antitumor activity of ASA404/everolimus combination treatment of orthotopic RENCA tumors

Finally, we examined the in vivo antitumor effects of ASA404, everolimus, and combination treatment on orthotopic murine RENCA tumors. Overall, therapy was well tolerated with minimal toxicities exhibited as determined by body weight (data not shown). Therapeutic efficacy was determined by measurement of tumor weights and quantification of necrosis in histologic sections in control and treated tumors. Figure 6A shows representative H&E sections of orthotopic RENCA tumors from control and treatment groups. Combination treatment with ASA404 and everolimus dramatically decreased the extent of this viable tumor rim compared with other treatment groups.

Figure 3. Combined BLI and MRI of orthotopic RENCA tumors. A, coronal and axial T2-weighted MR images (left) of a control mouse bearing orthotopic RENCA tumor in the right kidney (outlined in yellow). The contralateral kidney is outlined in red. Corresponding bioluminescence image of the same mouse is also shown. Histologic examination confirmed the invasive pattern of tumor growth observed on imaging. B, bar graph shows ΔR1 measurements of tumor and contralateral kidneys at the 4-hour time point (n = 3 per group). * indicates P < 0.05 compared with controls. C, axial T2-weighted (T2W) MR images and corresponding R1 maps of a representative mouse from control and each of the treatment groups at 4 hours posttreatment. An enlarged image of the tumor ROI is also shown.

Figure 4. Vascular response to ASA404/everolimus combination in vivo. Panel of images represent axial T2-weighted MR images and corresponding T1-enhancement (delta R1) maps of a mouse before (pretreatment) and 24 hours after a single treatment treated with ASA404 alone (A), everolimus alone (B), and combination (C). Postcontrast images at 24 hours posttreatment showed reduced enhancement compared with pretreatment images with all 3 groups. D, bar graph shows fBV measurements of tumors at the 24-hour time point (n = 3 per group). *** indicates P < 0.001 compared with baseline pretreatment values.
A significant reduction ($P < 0.05$) in tumor weight was seen following combination treatment compared with controls and ASA404 treatment alone (Fig. 6B). Control tumors exhibited minimal amounts of tumor necrosis (9.2 $\pm$ 2.9%; Fig. 6C). A significant increase in tumor necrosis was observed following treatment with ASA404 alone (46.0 $\pm$ 8.8%; $P < 0.01$) compared with untreated controls. Tumor necrosis following everolimus treatment was comparable with control tumors (6.3 $\pm$ 3.9; $P > 0.5$). Treatment with ASA404 alone resulted in marked necrosis of RENCA tumors, primarily restricted to the central regions of the tumor with viable tumor cells visible in the rim. Maximal tumor necrosis was seen following combination treatment (81.0 $\pm$ 6.0%) in comparison with untreated controls ($P < 0.001$) and single agent therapy (ASA404, $P = 0.02$ and everolimus, $P = 0.0002$).

Discussion

Targeting the neovasculature in patients with advanced and/or metastatic RCC has become the standard of care. The use of targeted therapies including angiogenesis inhibitors, TKIs and the mTOR inhibitors temsirolimus and everolimus has contributed to increased progression-free survival and overall survival in RCC patients (8, 24, 25). However, these therapies are often not curative and a majority of patients develop recurrent disease. Therefore, investigation into novel treatment approaches that could improve treatment outcome in RCC is warranted.

Tumor-VDAs represent a distinct class of drugs that target the established blood vessels of tumors and are actively being investigated for their therapeutic potential in preclinical studies and clinical trials in patients with solid tumors (12, 14, 15). Although the mechanism of action of these tumor-VDAs is not fully understood, agents such as ASA404 have been shown to exert both direct effects on the endothelium and indirect effects mediated by cytokines (17–19). Because angiogenesis inhibitors and VDAs target distinct vascular networks, combining VDAs with antiangiogenic agents has been proposed as a novel strategy in the treatment of solid malignancies. In support of this argument, studies have previously reported enhanced antitumor activity with the combination of a VDA and antiangiogenic agents such bevacizumab against RCC (26, 27). In this study, we investigated the activity of the tumor-VDA ASA404 in combination with the mTOR inhibitor everolimus.

Previous studies have shown the antiangiogenic and antitumor properties of everolimus in vitro and in vivo (10, 28, 29). We have previously shown that mTOR inhibition with rapamycin in combination with the HDAC inhibitor panobinostat greatly inhibited tumor angiogenesis by targeting HIF-1$\alpha$ in endothelial cell lines (30). Although everolimus and ASA404 have been shown to result in endothelial apoptosis when administered as single agents (10, 17), in this study, we observed enhanced inhibition of endothelial sprouting in 3D spheroid cultures. Combination of ASA404 and everolimus significantly enhanced cell death within endothelial cells.

The biological response of tumors to VDA treatment is typically characterized by early increases in vascular permeability followed by vascular collapse and cessation of blood flow leading to ischemia and tumor necrosis (18, 19, 21). In this study, we used a dual modality imaging approach to examine the vascular response of orthotopic RENCA tumors to everolimus, ASA404, and combination treatment. Although BLI enabled high-throughput visualization of tumor growth in vivo, it has limited clinical applicability. Therefore, quantitative estimates of vascular permeability and perfusion were obtained following mono- and combination therapy using MRI. Contrast-enhanced MRI is one of the most widely used imaging methods for assessment of angiogenesis in preclinical studies and in patients enrolled in clinical trials (22, 23, 31, 32). Several studies have highlighted the usefulness of MRI methods in the assessment of tumor vascular response to antiangiogenic agents and VDAs (22, 32–34). MRI parameters of tumor vascularity are also being actively investigated for their use as potential biomarkers of response in RCC patients (35–37). Consistent with previous observations in subcutaneous models (14, 15, 38), MRI detected an early and marked increase in vascular permeability following ASA404 treatment. Our MRI results also showed a significant reduction in IBV of RENCA tumors after a single dose of ASA404, everolimus,
and combination treatment. It is therefore likely that repeated doses of the VDA in conjunction with mTOR inhibition provide a cumulative assault on the tumor vascular network that results in catastrophic vascular damage subsequently leading to significant tumor ischemia. Our immunohistochemistry results provide supportive evidence of this increased tumor vascular damage following combination treatment. Consistent with the increased vascular damage, quantitative estimates of tumor necrosis were significantly greater with combination treatment compared with either monotherapy. Our in vivo studies carried out using immunohistochemical RCC xenografts also showed increased tumor growth inhibition following combination treatment.

Recently, Lara and colleagues published results from a randomized phase III trial of NSCLC patients treated with chemotherapy with or without ASA404 (39). This recent phase III trial followed a promising phase II trial where the median overall survival for patients treated with chemotherapy and patients treated with chemotherapy with ASA404 was 8.8 and 14 months, respectively (40). Unfortunately the phase III trial did not repeat the exciting results reported from the phase II trial. Overall survival for patients treated with chemotherapy and chemotherapy with ASA404 was 13.4 and 12.7 months, respectively (39). Although this data shed an unfavorable light on the clinical development of VDAs, it highlights several issues relevant to the clinical development of VDAs. Given the temporal effects of VDAs such as ASA404 on tumor vascular function, optimization of the VDA dose and schedule becomes a critical issue when examining the clinical activity of combination strategies. It is likely that the interaction between VDAs and mTOR inhibitors or RTKs may be strongly influenced by the sequence or schedule of administration given that both agents exert effects on tumor vasculature. To date most studies (including this study) have been conducted using concurrent administration of tumor-VDAs and RTKs or AIs. Alternative schedules or sequences warrant further investigation to develop a clinically feasible yet optimized drug administration protocol for maximal therapeutic benefit. In addition, lung and renal carcinomas have different

Figure 6. A, four micron RENCA tumor sections were stained with H&E for microscopic examination. Magnification, ×20 (left); ×40 (right). Scale bars, 50 μm. T, tumor; NK, normal kidney; N, necrosis (plus short arrows). Long arrows in combination panel indicate viable tumor rim. B, endpoint tumor weights; results for each treatment group represent mean ± SE (n = 3). ns, not significant; *, P < 0.0001. C, tumor necrosis was quantitated as described (see Materials and Methods). Each point represents mean ± SE. (ASA404, *, P = 0.02 and everolimus, **, P = 0.0002).
biology, so unfavorable results toward the treatment of lung cancer patients does not mean ASA404 will necessarily fail in the treatment of patients with RCC.

Tumor-VDAs exhibit moderate activity as single agents and a classic observation seen in preclinical model systems is the presence of a surviving rim of viable tumor cells in the periphery (14, 15). The hypoxia induced within the tumor, as a consequence of tumor vascular disruption, results in the activation of hypoxia inducible factor 1α (HIF-1α) and increased expression of HIF-target genes including those involved in angiogenesis such as VEGF (41). This has been suggested as a possible escape mechanism of tumors following VDA treatment. Combining VDAs with inhibitors of the angiogenesis signaling pathways, such as the PI3K/Akt/mTOR pathways often activated by receptor tyrosine kinases (42) offers an alternative to target the viable tumor rim resistant to VDA therapy. Our observations highlight the potential of combined targeting of neovasculature and established vasculature of tumors as a promising new treatment approach for the management of RCC.

The mTOR inhibitor everolimus is an approved drug in patients with progressive RCC following treatment with VEGR TKI (8). Results of the phase III trial in RCC patients revealed a median progression-free survival of 5.1 months with everolimus compared with 1.9 months in the placebo arm (43). Despite this observed clinical benefit, additional treatment in these patients is eventually necessary. To this end, therapeutic strategies simultaneously targeting the VEGF and the mTOR pathways to achieve greatest anti-tumor effect have been tested in preclinical models (28). Combinations of anti-VEGF therapies and mTOR inhibitors have reported some clinical benefit but also increased toxicities as compared with single agents, resulting in significant dose reductions (44). Thus, the combination of a VDA and an mTOR inhibitor is also compelling in view of the lack of overlapping toxicities and the possibility of administering the 2 agents at doses associated with maximal antitumor activity. The disruptive effect of this combination on established blood vessels and in an orthotopic RCC model further suggests the potential use for this therapeutic strategy also on primary tumors in the neoadjuvant clinical setting. Given these advantages, clinical investigation into the combination of VDAs with mTOR inhibitors in RCC is warranted.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Acknowledgments

The authors thank Dean Evans and Paul McSheehy from Novartis Institute of Biomedical Research, Basel, Switzerland, for insightful discussions regarding experimental design and for the supply of everolimus and ASA404.

Grant Support

This study was in part supported by the Flight Attendant Medical Research Institute (R. Pili) and the NIH-1R01CA135321-01A1 (R. Pili). The work was also supported by a grant from the Roswell Park Alliance Foundation (M. Seshadri) and used shared resources supported by RPF’s Center Support Grant of the National Cancer Institute P30CA16056 (D.L. Trump). The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked advertisement in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Received September 19, 2011; revised November 4, 2011; accepted November 7, 2011; published OnlineFirst November 14, 2011.

References


Molecular Cancer Therapeutics

Vascular Disruption in Combination with mTOR Inhibition in Renal Cell Carcinoma

Leigh Ellis, Preeti Shah, Hans Hammers, et al.


Updated version
Access the most recent version of this article at:
doi:10.1158/1535-7163.MCT-11-0748

Cited articles
This article cites 44 articles, 16 of which you can access for free at:
http://mct.aacrjournals.org/content/11/2/383.full#ref-list-1

Citing articles
This article has been cited by 2 HighWire-hosted articles. Access the articles at:
http://mct.aacrjournals.org/content/11/2/383.full#related-urls

E-mail alerts
Sign up to receive free email-alerts related to this article or journal.

Reprints and Subscriptions
To order reprints of this article or to subscribe to the journal, contact the AACR Publications Department at pubs@aacr.org.

Permissions
To request permission to re-use all or part of this article, contact the AACR Publications Department at permissions@aacr.org.