Selective Disruption of Rb–Raf-1 Kinase Interaction Inhibits Pancreatic Adenocarcinoma Growth Irrespective of Gemcitabine Sensitivity

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Abstract

Inactivation of the retinoblastoma (Rb) tumor suppressor protein is widespread in human cancers. Inactivation of Rb is thought to be initiated by association with Raf-1 (C-Raf) kinase, and here we determined how RRD-251, a disruptor of the Rb–Raf-1 interaction, affects pancreatic tumor progression. Assessment of phospho-Rb levels in resected human pancreatic tumor specimens by immunohistochemistry (n = 95) showed that increased Rb phosphorylation correlated with increasing grade of resected human pancreatic adenocarcinomas (P = 0.0272), which correlated with reduced overall patient survival (P = 0.0186). To define the antitumor effects of RRD-251 (50 μmol/L), cell-cycle analyses, senescence, cell viability, cell migration, anchorage-independent growth, angiogenic tubule formation and invasion assays were conducted on gemcitabine-sensitive and -resistant pancreatic cancer cells. RRD-251 prevented S-phase entry, induced senescence and apoptosis, and inhibited anchorage-independent growth and invasion (P < 0.01). Drug efficacy on subcutaneous and orthotopic xenograft models was tested by intraperitoneal injections of RRD-251 (50 mg/kg) alone or in combination with gemcitabine (250 mg/kg). RRD-251 significantly reduced tumor growth in vivo accompanied by reduced Rb phosphorylation and lymph node and liver metastasis (P < 0.01). Combination of RRD-251 with gemcitabine showed cooperative effect on tumor growth (P < 0.01). In conclusion, disruption of the Rb–Raf-1 interaction significantly reduces the malignant properties of pancreatic cancer cells irrespective of their gemcitabine sensitivity. Selective targeting of Rb–Raf-1 interaction might be a promising strategy targeting pancreatic cancer.

Introduction

Pancreatic adenocarcinoma remains the fourth leading cause of cancer-related deaths (1). Even after potential curative surgery and adjuvant therapies, the overall 5-year survival rate remains approximately 5% (2). In addition, chemotherapy with gemcitabine alone provides poor long-term outcome, with the possible acquisition of gemcitabine resistance by a variety of molecular aberrations that have not been fully defined (3, 4). Therefore, further understanding the molecular mechanisms involved in the genesis, progression, chemoresistance, and metastasis of pancreatic cancers might lead to the development of more effective therapeutic strategies.

The retinoblastoma (Rb) tumor suppressor protein is the major regulator of the mammalian cell-cycle progression (5–7). Rb prevents cell-cycle progression by physically interacting with E2F family of transcription factors repressing their transcriptional activity (8). Phosphorylation of Rb protein by cyclin-dependent kinases, mainly Cdk2, Cdk4, and Cdk6, leads to the dissociation of E2Fs from Rb, enabling them to induce downstream target genes that are necessary for cell-cycle progression (7). Thus, agents that can prevent Rb phosphorylation and maintain its functional state can be expected to have a cytostatic effect with subsequent antitumor activities (5).

Although Rb phosphorylation is mediated mainly by cyclin-dependent kinases, Raf-1 could bind and phosphorylate Rb early in the cell cycle, facilitating subsequent phosphorylation and complete inactivation (5, 9). An 8-amino-acid peptide inhibiting Rb–Raf-1 interactions confirmed this hypothesis (10), and development of a small-molecule inhibitor of the Rb–Raf-1 interaction, RRD-251, prevented Rb phosphorylation and subsequent growth of lung cancer and melanoma (7, 11). In invasive pancreatic adenocarcinoma, Rb expression correlates with...
histologic grade and nodal involvement (12, 13), therefore promoting investigations toward therapies against Rb phosphorylation.

Here, we show that Rb phosphorylation correlates with more advanced disease in human pancreatic tumor tissues which correlates with poor overall survival. Inhibition of Rb phosphorylation with RRD-251 led to an inhibition of proliferation, migration, and invasion in a pancreatic cancer cell lines, including highly metastatic cells that are resistant to gemcitabine. RRD-251 also prevented the in vivo growth and metastasis of pancreatic cancer cells xenograft models. Importantly, the combination therapy of gemcitabine and RRD-251 showed chemotherapeutic sensitization in xenograft models. These results suggest that targeting the Rb–Raf-1 interaction might be a potential avenue to combat pancreatic cancer.

Materials and Methods

Cell lines and reagents
PANC-1 and Mia-PaCa-2 human pancreatic cancer cells were obtained from American Type Culture Collection and were used within 6 months; they have been re-authenticated by STR analysis. The L3.6pl metastatic variant pancreatic cancer cell line was derived as previously described (14, 15). The cells were maintained in culture in Dulbecco’s Modified Eagle’s Medium supplemented with 10% FBS (HyClone) and 0.6% penicillin/streptomycin/amphotericin-B (HyClone). RRD-251 was suspended in dimethyl sulfoxide (DMSO) as previously described (11). Gemcitabine (Eli Lilly) was suspended in Dulbecco’s PBS (D-PBS).

Selection of L3.6plGemRes gemcitabine-resistant pancreatic cancer cells
Selection of L3.6plGemRes gemcitabine-resistant pancreatic cancer cells was conducted as previously described (16). L3.6pl gemcitabine-sensitive cells were exposed to 5 μmol/L of gemcitabine. The dose was steadily increased by 5 μmol/L increments every 2 days to maximal concentration of 30 μmol/L, approximately 12-fold greater than the IC50. Single colonies of gemcitabine-resistant clones were isolated and expanded for further analysis. Persistence of gemcitabine resistance was confirmed by maintenance of cells without gemcitabine for 6 weeks followed by return to maintenance gemcitabine concentrations (5 μmol/L) with no effect on cellular proliferation or apoptosis. Authentication of this cell line showed that its short tandem repeat profile is identical to the parental cell line, L3.6pl.

Lysate preparation, immunoprecipitation, and Western blotting
Lysates were prepared from cells and tumor tissues as previously described (11). Physical interaction between Rb-Raf-1 and Rb-E2F1 was analyzed by immunoprecipitating Raf-1 and E2F1 as previously described (10). Monoclonal Rb and Raf-1 antibodies (BD Transduction Laboratories) and E2F1 (Santa Cruz Biotechnology), polyclonal phosphorylated Rb and PARP antibodies (Cell Signaling Technology), Mcl-1, Bcl-2, and Bax antibodies (Santa Cruz Biotechnology), β-actin (Sigma-Aldrich) were used for Western blot analyses.

Cell-cycle and apoptotic analyses by flow cytometric analyses
Cells were serum starved for 48 hours and subsequently serum-stimulated in the presence or absence of RRD-251 for 18 hours. Cells were washed in D-PBS, harvested, centrifuged, and pellet resuspended in 0.1 mL of citrate/DMSO buffer. Samples were processed per Vindelov method and cell-cycle analysis was conducted by flow cytometry (7, 17). For detection of apoptosis, cells were treated with RRD-251 for 24 hours and apoptosis was detected by 7-aminoactinomycin D (7-AAD) and Annexin V staining (BD Pharmingen) as previously described (18).

Cell viability/cytotoxicity and senescence assays
Cell viability was quantified by MTT assay (Trivigen). Cells were allowed to adhere overnight. Cells were treated with RRD-251 (10–100 μmol/L) or DMSO in complete media and viability assayed after 48 hours using published protocols (19). Senescence was determined after treatment with RRD-251 (50 μmol/L), cdk inhibitor PD0332991 (2.5 μmol/L; Selleck Chemical) or vehicle control (DMSO) for 48 hours. The cells were stained with β-galactosidase per senescence staining kit protocols (Cell Signaling). The blue senescent cells were quantified by counting 4 different fields (20×).

Soft agar colony formation assay
Five thousand cells were suspended in 0.3% agarose and layered on top of 0.6% bottom agarose in 12-well sterile plates (Corning). Plates were covered with 1 mL of complete medium with 50 μmol/L RRD-251 (in DMSO) or DMSO and incubated for 3 weeks. RRD-251 was refreshed twice weekly in complete media. The colonies were stained with MTT as previously described (7).

Wound-healing and invasion assays
Cells grown to 90% confluency were scratched at 3 different areas. Cells were treated with RRD-251 (50 μmol/L) or DMSO control for 18 hours, and multiple images were taken before and after treatment. For invasion assays, cells were pretreated with 50 μmol/L RRD-251 for 4 hours, and 20,000 cells were plated in the upper chamber of the filter in 10% FBS and 0.1% bovine serum albumin containing media (Sigma). Media containing 20% FBS was placed in the lower well as an attractant. After 18 hours, the filters were fixed in methanol and stained with hematoxylin. Invading cells were imaged and quantified by counting 4 different fields.

Angiogenic tubule formation assay
Matrigel (Collaborative Biomedical Products) was used to assess the differentiation of human umbilical
vascular endothelial cells (HUVEC) into capillary tube-like structures (10). Matrigel was added to 96-well tissue culture plates, followed by incubation at 37°C for 60 minutes to allow polymerization. Subsequently, 1 × 10^4 HUVECs were seeded in EGM2 medium (Clonetics) supplemented with 5% FBS in the presence or absence of 20, 50, and 100 μmol/L concentrations of RRD-251 and incubated for 18 hours at 37°C. Capillary tube formation was assessed using a Leica DMIL phase contrast microscope.

Real-time PCR

HUVECs were serum-starved for 24 hours, pretreated with RRD-251 at indicated doses, and subsequently stimulated with VEGF (100 ng/mL). Total RNA was isolated using the RNasy Kit (Qiagen). Levels of FLT-1 and KDR mRNA were analyzed by quantitative reverse transcription PCR. The primers used for amplifying FLTI mRNA were FLT-1 F5′ AGCGATTGCATTGACCTGCC and KDR F5′ GGTACGAATCGACCGAATC and for KDR mRNA the primers used were KDR F5′ CATTGACCTGCCGAAT, KDR R 5′ CCGAATCTCAAGACTG. Data were normalized using 18S rRNA as internal control, and the fold change in the expression levels was determined as described (20).

Mouse xenograft experiments

For subcutaneous implantation, 1 × 10^6 pancreatic cancer cells were implanted in the subcutaneous flank tissue of 6-week-old female athymic nude mice (Charles River Laboratories) using a minimum of 6 mice per group. The tumor growth was established (100 mm^3), RRD-251 was administered intraperitoneally daily at 50 mg/kg in DMSO vehicle. For gemcitabine treatment, intraperitoneal dosing of gemcitabine at 250 mg/kg was scheduled 251 was administered intraperitoneally daily at 50 mg/kg for orthotopic implantation, a left abdominal flank incision was conducted with exteriorization of the spleen and pancreas, and 2.5 × 10^6 cells were injected into the subcapsular region of the body of the pancreas as previously described (19). One week after injections, mice were treated with RRD-251 or DMSO control daily. Mice were euthanized 4 weeks after implantation and primary tumors, regional peri-pancreatic (celiac and para-aortic) lymph nodes, and livers were harvested for further analyses. All animal experiments were carried out with approval from the institutional IACUC.

Pancreatic cancer tissue microarrays

All cases of resected pancreatic ductal adenocarcinoma (PDAC) used to generate tissue microarrays (TMA) were resected at the H. Lee Moffitt Cancer Center and Research Institute from 1987 to 2006; these studies were conducted under a protocol approved by the USF IRB. Two separate cores, 0.6 cm in diameter, were obtained for each area of carcinoma as well as from the nonmalignant areas. Sections of the TMA were stained with hematoxylin and eosin (H&E) using standard techniques (19). The TMAs were reviewed and grade (I–IV) assigned to the each core containing carcinoma using a standard grading system.

Immunohistochemistry

Immunohistochemical staining was conducted using a Ventana Discovery XT automated system as per manufacturer’s protocol with proprietary reagents (21). Primary antibody against phospho-Rb, (Cell Signaling) and CD31 antibody (Abcam) was used for immunohistochemistry. Stained slides were scanned on an Ariol SL-50 Automatic Scanning System. Both the intensity and percentage of cells expressing phospho-Rb were assessed. The intensity of nuclear staining was assessed as 0 (absent), 1+ (weak), 2+ (moderate), and 3+ (strong) for pRb. Each core was assigned a histoscore consisting of the sum of the product of each intensity and the percentage of cells positive at that intensity [histoscore = (0 × 0) + (1 × % cells) + (2 × % cells) + (3 × % cells) + (4 × % cells)].

Statistical analyses

Statistical analysis was conducted using 2-tailed Student t test. Experiments were carried out in triplicate, and values were considered significant when the P < 0.05. TMA immunohistochemical analyses are expressed as the mean ± SD. Correlation between staining extent and intensity was determined by Spearman correlation coefficient. One-way ANOVA was used to correlate pRB score with grade. Disease-specific survival was estimated by the Kaplan–Meier method.

Results

Rb phosphorylation correlates with tumor grade/differentiation in human pancreatic tumor specimens

To determine whether Rb phosphorylation correlates with tumor grade pancreatic cancer TMAs were stained for phospho-Rb. Assessment of grade within each core showed the following distribution: nine grade I carcinomas (well-differentiated), 55 grade II carcinomas (moderately differentiated), 31 grade III carcinomas (including one adenosquamous carcinoma shown in poorly differentiated, Fig. 1A, top) and 1 grade IV carcinoma. All grades showed intensity ranging from 0 to 3 and a pRb-staining product (score) ranging from 0 to 300. The mean pRb score for each grade is as follows: 107.8 for grade I (107.8 ± 59.1), 131.1 for grade II (131.1 ± 86.6), and 177.4 for grade III and IV combined (177.4 ± 82.7). Comparison of phospho-Rb levels with grade of PDAC stratified into 2 categories (low grade = grades I and II, high grade = grades III and IV) showed a statistically significant difference in expression (P = 0.0272; Fig. 1A, bottom), with increased Rb phosphorylation correlating with...
higher grade. Overall survival correlated with grade using our two-tiered classification ($P = 0.0186$). Thus, high-grade PDAC, which correlates with poorer survival, are tumors that have more phosphorylated Rb; future studies on larger cohorts of patients will be needed to confirm these correlations.
Disruption of Rb–Raf-1 interaction inhibits anchorage-independent growth

As clinical samples suggested a correlation of Rb phosphorylation with reduced differentiation, we examined whether RRD-251 affected Rb phosphorylation. Western blot analyses conducted on L3.6pl, L3.6plGemRes, PANC-1, and Mia-PaCa-2 cells treated with 50 μmol/L RRD-251 for 24 hours showed a reduction in the slower migrating hyperphosphorylated form of Rb (Fig. 1B, top). To examine whether this correlated with a disruption of Rb–Raf-1 binding, cells were serum-starved for 48 hours and serum-stimulated for 2 hours in the presence or absence of RRD-251. Immunoprecipitation and Western blot (IP-WB) analysis showed that RRD-251 treatment led to a significant reduction in the serum-induced binding of Raf-1 to Rb (Fig. 1B, bottom). RRD-251 did not disrupt the binding of E2F1 to Rb (Fig. 1C), as we had seen in other cell lines. We next examined the effects of RRD-251 on the adherence-independent growth of PANC-1, Mia-PaCa-2, and L3.6pl metastatic variants. RRD-251 significantly inhibited anchorage-independent growth of cells in soft agar (Fig. 1D). Structure of RRD-251 is shown in Fig. 1E. These results suggest that RRD-251 can disrupt Rb–Raf-1 binding and Rb-phosphorylation and significantly inhibit anchorage-independent growth of cell lines.

Disruption of Rb–Raf-1 interaction results in inhibition of proliferation and induction of senescence

Previous studies showed that RRD-251 induces G1 arrest in lung cancer cells but induces apoptosis in melanoma cells (7). To determine how RRD-251 affects pancreatic cancer cells, PANC-1 and Mia-PaCa-2, metastatic variant L3.6pl, and L3.6plGemRes cells were treated with 50 μmol/L RRD-251 for 48 hours. Western blot analysis showed cleavage of PARP indicative of apoptosis, in both PANC-1 and Mia-PaCa-2 cells; there was no significant apoptosis in the metastatic cell lines (Fig. 2A, top). RRD-251 treatment of L3.6pl, MIA-PaCa-2, and PANC-1 cells and showed a decrease in levels of anti-apoptotic proteins Bcl-2 and Mcl-1 and increased the pro-apoptotic protein Bax (Fig. 2A, bottom). Furthermore, determination of apoptosis by Annexin V by flow cytometry determined that RRD-251 could result in significant induction of apoptosis in PANC-1 (33.4% early and 50.8% late apoptosis) and Mia-PaCa-2 (10.4% early and 14.1% late apoptosis), but no significant change in L3.6pl and L3.6plGemRes cells when compared to controls (Supplementary Figs. S1 and S2 and Tables S1 and S2). As metastatic L3.6pl cells were resistant to RRD-251–induced apoptosis, further experiments were carried out to assess how RRD-251 inhibited the growth of L3.6pl and L3.6plGemRes cells. L3.6pl and L3.6plGemRes were exposed to different concentrations of RRD-251 (10—100 μmol/L) and cell viability was quantified after 48 hours. Viability of L3.6pl cells was significantly reduced in a dose-dependent manner (P < 0.01; Fig. 2B), whereas L3.6plGemRes cells was affected to a lesser extent. As RRD-251 did not induce apoptosis in these cells, we examined whether the inhibitory effects could be due to an arrest in cell-cycle progression (7). As shown in Fig. 2C, there was a 65% reduction in S-phase and 50% increase in G1 phase in L3.6pl cell populations treated with RRD-251 (left) and a 61% reduction in S-phase and 54% increase in G1 phase in L3.6plGemRes cells (Fig. 2C, right). Attempts were also made to assess whether the cell-cycle arrest also coincided with induction of cellular senescence. To further elucidate the mechanism of RRD-251, staining for senescence-associated β-galactosidase showed that RRD-251 significantly induced cellular senescence (Fig. 2D) to levels induced by CDK inhibitor PD0332991, a known inducer of senescence (22, 23). These results suggest that RRD-251 induces both cell-cycle arrest and cellular senescence in metastatic and gemcitabine-resistant pancreatic cancer cells.

RRD-251 enhances the effects of gemcitabine to promote apoptosis and inhibit anchorage-independent growth in gemcitabine-resistant L3.6plGemRes

To determine the effect of combination therapy of RRD-251 with gemcitabine (Fig. 3A), acquired gemcitabine resistance was confirmed by continued growth and resistance to PARP cleavage of L3.6plGemRes cells in the presence of gemcitabine when compared to parental L3.6pl (Fig. 3B). As RRD-251 did not induce apoptosis in the metastatic variant L3.6pl or L3.6plGemRes, we examined whether combining RRD-251 with gemcitabine had an effect. Toward this purpose, L3.6plGemRes cells were exposed to gemcitabine (5 μmol/L), RRD-251 (50 μmol/L), or in combination. While gemcitabine resulted in a 70% decrease in viability of the L3.6pl parental cell line, RRD-251 alone or in combination with gemcitabine showed a 61% and 87% decrease in viability respectively, suggesting a sensitization to combination therapy. In addition, while gemcitabine alone did not have an inhibitory effect in the L3.6plGemRes, but rather a 1.3-fold increase in cell viability, RRD-251 alone resulted in a 50% reduction in its viability. Combination of RRD-251 with gemcitabine further inhibited the viability by 69% (Fig. 3C), suggesting an enhanced effect with combination therapy on gemcitabine-resistant cells. To examine whether this reduction in viability was due to apoptosis, PARP cleavage was examined by Western blotting. Gemcitabine or RRD-251 alone did not induce PARP cleavage or changes in apoptotic proteins in L3.6plGemRes cells, but treatment with combination of RRD-251 and gemcitabine resulted in PARP cleavage; this correlated with decreased expression of anti-apoptotic proteins Bcl-2 and Mcl-1, an increase in pro-apoptotic protein Bax (Fig. 3D, top). To confirm our PARP cleavage results, we conducted Annexin V staining flow cytometry on L3.6pl and L3.6plGemRes pancreatic cancer cells treated with gemcitabine, RRD-251, or in combination. Our results show only combination treatment with RRD-251 and gemcitabine significantly induced apoptosis (19.8% early and 45.5% late apoptosis) in L3.6plGemRes gemcitabine-resistant cells.


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Although experiments with RRD-251 alone showed a significant reduction in anchorage-independent growth in L3.6pl cells, a less robust effect was observed in L3.6pl GemRes cells; but combination of RRD-251 and gemcitabine showed almost complete abrogation of growth (Fig. 3D, bottom). Overall, these results suggest the inhibitory effects on RRD-251 alone were likely due to cell-cycle arrest in the metastatic pancreatic cancer cell lines MIA-PaCa-2 and PANC-1. (Supplementary Fig. S2 and Table S2).

Figure 2. Disruption of Rb-Raf-1 kinase interactions with RRD-251 induces cell-cycle arrest, inhibits proliferation, and induces senescence in metastatic/chemoresistant pancreatic cancer variants. A, pancreatic cancer cells treated with RRD-251 show PARP cleavage, along with a decrease in anti-apoptotic proteins Bcl-2, Mcl-1 and increase in pro-apoptotic protein Bax (bottom). B, RRD-251 significantly affects cell proliferation/viability in a dose-dependent manner on L3.6pl and L3.6plGemRes metastatic pancreatic cancer cells (**, P < 0.01). C, cell-cycle analysis shows a significant arrest in S-phase entry in metastatic (left) and gemcitabine-resistant variants treated with RRD-251 (right). D, measured (left) and representative images (right) of senescence in L3.6pl and L3.6plGemRes metastatic pancreatic cancer cells treated with RRD-251 comparable to positive control CDK4 inhibitor PD0332991.
RRD-251 enhances the effects of gemcitabine. A, chemical structure of gemcitabine. B, gemcitabine has no effect on L3.6plGemRes cell proliferation and does not show PARP cleavage in the presence of gemcitabine when compared to parental gemcitabine-sensitive L3.6pl. C, L3.6pl and L3.6plGemRes pancreatic cancer cells treated with RRD-251 showed a significant decrease in cell viability/proliferation with augmented inhibitory effect noted with gemcitabine combination (*, P < 0.001). D, L3.6plGemRes cells treated with combination RRD-251 and gemcitabine showed robust PARP cleavage (top). There was a decrease in anti-apoptotic proteins Bcl-2, Mcl-1 and increase in pro-apoptotic protein Bax (middle). RRD-251 significantly inhibits anchorage-independent growth of L3.6plGemRes cells and enhances the effects of gemcitabine chemotherapy (bottom). RRD-251 significantly inhibited the migratory (E) and invasive (F, qualitative top, quantitative bottom) ability of metastatic variant L3.6pl and gemcitabine-resistant L3.6plGemRes while showing further inhibition of invasion with the addition of gemcitabine (P < 0.001).
pancreatic cancer cell lines, but combination with gemcitabine induced apoptosis in gemcitabine-resistant L3.6plGemRes cells.

Rb–Raf-1 kinase disruption inhibits migration, invasion, and angiogenic potential

Wound-healing assays were conducted to determine whether RRD-251 alone or in combination with gemcitabine affects migration of L3.6pl and L3.6plGemRes cells. While gemcitabine significantly inhibited the ability of L3.6pl cell to migrate, the L3.6plGemRes continued to migrate in the presence of gemcitabine. RRD-251 alone or combination with gemcitabine significantly reduced the migratory capacity of both populations (Fig. 3E). As shown in Fig. 3F, while gemcitabine marginally increased invasion in the L3.6plGemRes cells, RRD-251 alone resulted in a 74% reduction in the invasion of both L3.6pl and L3.6plGemRes cells. Combination of RRD-251 with gemcitabine resulted in 96% and 91% reduction in the invasive capacity of L3.6pl and L3.6plGemRes cells, respectively ($P<0.001$; Fig. 3F). In addition, treatment with RRD-251 led to a marked inhibition of angiogenic tubule formation (Fig. 4A, left). Previously, we had observed that VEGF, FLT-1, and KDR receptors have E2F-binding sites, which respond to the Rb–E2F pathway (20). In our studies, it was found that RRD-251 significantly inhibited the expression of FLT-1 and KDR, potentially leading to the inhibition of angiogenic tubule formation (Fig. 4A, right). It appears that RRD-251 can not only affect the viability of pancreatic cancer cells but also affect processes like migration, invasion, and angiogenesis, which facilitate the progression and metastasis of pancreatic cancers.

RRD-251 inhibits primary tumor growth in subcutaneous and orthotopic xenograft models and significantly affects metastatic potential in vivo

We next determined the effects of RRD-251 on pancreatic cancer cells in vivo using subcutaneous and orthotopic xenograft models. L3.6pl cells were implanted bilaterally on the flanks of athymic nude mice in the subcutaneous model; 50 mg/kg of RRD-251 or vehicle was administered intraperitoneally daily after the implanted tumors reached 100 mm$^3$ size. After 14 days of treatment, tumor growth in the RRD-251 group (117 ± 20 mm$^3$) was significantly lower than vehicle control (1,094 ± 67 mm$^3$, $P<0.01$; Fig. 4B). This difference in tumor size was confirmed by measurements ex vivo (Fig. 4B, inset). IP/WB analysis of resected tumors showed a significant reduction in Rb bound to Raf-1 in the RRD-251–treated mice (Fig. 4B, left). Furthermore, decreased immunohistochemical staining for phospho-Rb was observed in tumors from mice treated with RRD-251 (Fig. 4C, left). Quantification of the staining showed a significantly decreased level of phospho-Rb in the tumor samples treated with RRD-251 (44.54% ± 6.33% negative weak, 5.23% ± 2.49% strong) when compared to the control tumor samples (16.51% ± 3.3% negative weak, 51.17 ± 6.29% strong; Fig. 4C, right). To determine whether RRD-251 affected the angiogenesis in the xenografted pancreatic cancers, tumors were stained for CD31 (Fig. 4D, left). Supporting our in vitro results, tumors treated with RRD-251 showed a 14-fold reduction in microvasculature (Fig. 4D, right). These results suggest that inhibition of tumor growth by RRD-251 correlates with a disruption of the Rb–Raf-1 interaction, decrease in Rb phosphorylation, and angiogenesis.

An orthotopic model was used to investigate whether RRD-251 could prevent the metastasis of pancreatic tumors. Metastatic L3.6pl pancreatic cancer cells were implanted in the pancreas of nude mice; after 1 week of inoculation, the mice were randomized into 2 groups and treated as described above. After 3 weeks of treatment, mice were euthanized, and primary tumor growth in pancreas and metastasis to liver and lymph nodes were analyzed. RRD-251 significantly reduced primary tumor size (Fig. 5A) and also significantly affected the tumors ability to metastasize to lymph nodes and liver as represented by H&E (Fig. 5B). Tumor volume was reduced by approximately 90% and lymph node and liver metastases reduced by 83% and 100%, respectively, in mice treated with RRD-251. In addition, Rb phosphorylation (p-Rb) was significantly higher at metastatic tumor sites than adjacent normal tissues (Fig. 5C), suggesting that Rb inactivation contributes to metastatic potential.

RRD-251 enhances the ability of gemcitabine to inhibit primary tumor growth

Attempts were next made to determine whether RRD-251 could improve the effects of gemcitabine and inhibit the growth of gemcitabine resistant cells in vivo. A subcutaneous xenograft model using the gemcitabine-sensitive L3.6pl and resistant L3.6plGemRes was used for this purpose. L3.6pl and L3.6plGemRes were implanted in the left and right flanks, respectively. After tumors grew in each flank to approximately 100 mm$^3$, gemcitabine (250 mg/kg, 3 times a week), RRD-251 (50 mg/kg daily), combination of gemcitabine and RRD-251 or DMSO/PBS vehicle were administered intraperitoneal. Tumors were measured every 2 to 4 days. After 16 days of treatment, the tumors were harvested. While gemcitabine significantly inhibited primary tumor growth in the gemcitabine-sensitive L3.6pl cells (Fig. 6A), L3.6plGemRes tumor growth was heightened by gemcitabine (Fig. 6B). RRD-251 alone significantly affected the growth of tumor growth regardless of chemosensitivity; in addition, combinations of RRD-251 with gemcitabine resulted in further tumor regression and almost complete tumor abrogation in both gemcitabine-sensitive and -resistant tumors (Fig. 6C and D). These results suggest that combining RRD-251 with gemcitabine could be an effective therapy against pancreatic cancer.

Discussion

Although Rb itself has shown mutations in various malignancies, the majority of tumors harbor mutations.
RRD-251 Inhibits Pancreatic Tumor Growth and Metastasis

A

Control

25 µmol/L 50 µmol/L 100 µmol/L

RRD-251

B

DMSO Control

RRD251 50mpk

Volume (mm$^3$)

0 2 6 8 12 14

Days

* = P < 0.01

C

H&E p-Rb

Control

RRD-251 (50mpk)

D

H&E CD31

Control

RRD-251 (50mpk)

CD31 Quantification

% CD31 Quantification

Control RRD-251

RRD-251

* P < 0.001
Results were quantified in each group and represented as negative weak and strong expression (1< P < 0.01). Inset, size differences were evident in vivo and ex vivo. Right, disruption of the Rb–Raf-1 interaction by RRD-251 in the tumor lysates was observed in an IP-WB experiment. C, immunohistochemical analysis of tumor samples showed a significant reduction in Rb phosphorylation in RRD-251–treated mice (left). Results were quantified in each group and represented as negative weak and strong expression (1< P < 0.01; right). D, CD31 staining showed an inhibitory effect of RRD-251 on angiogenesis in vivo (left). CD31 quantification was conducted on tumor samples of mice treated with RRD-251 and control as previously described (1< P < 0.001; right).

Figure 5. RRD-251 inhibits orthotopic tumor growth and metastasis. A, mice treated with RRD-251 had a significant decrease in primary orthotopic tumor growth (1, P< 0.01). B, representative H&E tumor samples (T) of mice treated with RRD-251 shows the loss of metastases (M) to liver and lymph nodes adjacent to normal tissue (N). C, expression levels of phospho-Rb (p-Rb) are higher in lymph node and liver metastatic sites (M) of control mice when compared to the unaffected lymph node and liver tissue (N) of mice treated with RRD-251.
proliferation, senescence, and apoptosis. As our results show, RRD-251 has not been found to affect the binding of E2F1 to Rb. We propose that the dissociation of Brg1 from Rb, as Rb remains hypophosphorylated. Therefore, it is likely that Rb phosphorylation, which has been established as a cellular target of the Raf-1 kinase, could be a suitable target for pancreatic adenocarcinoma. Our present studies show that disruption of the Rb–Raf-1 kinase interaction affects Rb phosphorylation and the malignant properties of pancreatic adenocarcinoma cells.

Similar to previous reports in melanoma (7), exposure of RRD-251 resulted in apoptosis of pancreatic cancer cell lines by affecting the levels of anti-apoptotic Bcl-2 and Mcl-1 and pro-apoptotic Bax proteins. These inhibitory effects of RRD-251 with gemcitabine were also observed in anchorage-independent cell growth, migration, and invasion, which are key features for carcinogenesis and malignant transformation. The clinical challenge in management of pancreatic cancer with aggressive phenotypes that result in early metastases is the resistance to the current first-line chemotherapeutic agent, gemcitabine. In most preclinical models of pancreatic cancer, gemcitabine chemotherapy results in suppression of cell growth and apoptosis. Unfortunately, the continued use of gemcitabine can result in the development of chemotherapeutic resistance and overexpression of a variety of survival mechanisms, including the activation of the Akt/mTOR pathway. Recent evidence supports gemcitabine activation of a variety of proliferative and anti-apoptotic pathways in cancer cells (34). G2–M cell-cycle arrest with cyclin-dependent kinase inhibitors has been shown to induce senescence (22, 23) and also inhibit pro-apoptotic pathways that might contribute to
chemoresistance (35). Our studies show that while L3.6pl and L3.6plGemres resist the apoptotic effects of RRD-251, this therapy induces senescence. An apoptotic effect was observed when combined with gemcitabine in L3.6plGemres, with a re-establishment of sensitivity to gemcitabine observed in the parental L3.6pl cells. It is conceivable that induction of senescence with RRD-251 might inhibit pro-apoptotic pathways, such as Akt/mTOR, and restore sensitivity in otherwise chemoresistant phenotypes. We also propose that antitumor effects of RRD-251 were exerted in partly limiting angiogenesis. This is supported by the studies showing that Raf-1 kinase contributes to angiogenesis (36, 37); this might involve inactivation of Rb with subsequent induction of E2F–mediated FLT-1 and KDR transcriptional activation.

Identification of RRD-251 as a selective inhibitor of Rb–Raf-1 interaction is an example of targeting protein–protein interactions for pancreatic cancer therapy. In this study, we show the importance of a small molecule that can maintain the tumor suppressor function of Rb by disrupting its physical interaction with other proteins and also enhance the effects of gemcitabine chemotherapy. We believe these discoveries will ultimately lead to new therapeutic strategies to combat cancer.

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

References


Molecular Cancer Therapeutics

Selective Disruption of Rb–Raf-1 Kinase Interaction Inhibits Pancreatic Adenocarcinoma Growth Irrespective of Gemcitabine Sensitivity

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