Enhancement of 5-Fluorouracil-induced In Vitro and In Vivo Radiosensitization with MEK Inhibition

Mary Ellen Urick1, Eun Joo Chung1, William P. Shield III1, Naamit Gerber1, Ayla White1, Anastasia Sowers2, Angela Thetford2, Kevin Camphausen1, James Mitchell2, and Deborah E. Citrin1

Abstract

Purpose: Gastrointestinal cancers frequently exhibit mutational activation of the Ras/MAPK pathway, which is implicated in resistance to ionizing radiation (IR) and chemotherapy. Concurrent radiotherapy and 5-fluorouracil (5-FU) based chemotherapy is commonly used for treatment of gastrointestinal malignancies. We previously reported radiosensitization with selumetinib, an inhibitor of MEK1/2. The purpose of the current study was to evaluate if selumetinib could enhance radiosensitivity induced by 5-FU.

Experimental Design: Clonogenic survival assays were carried out with the HT29 (colorectal), HCT116 (colorectal), and MiaPaca-2 (pancreatic) cell lines using pre-IR treatment with selumetinib, 5-FU and 5-FU + selumetinib. Cell proliferation was determined using a tetrazolium conversion assay. Mitotic catastrophe and DNA repair were analyzed using immunocytochemistry. Flow cytometry was used to analyze cell cycle and apoptosis. Growth delay was used to determine effects of 5-FU + selumetinib on in vivo tumor radiosensitivity.

Results: Pre-IR treatment with 5-FU + selumetinib significantly decreased clonogenic survival compared with either agent alone. Dose modifying factors at a surviving fraction of 0.1 for 5-FU + selumetinib was 1.78, 1.52, and 1.3 for HT29, HCT116, and MiaPaca-2, respectively. Cell proliferation was decreased by treatment with selumetinib + 5-FU as compared with single agent treatment regardless of treatment sequencing. Enhancement of 5-FU cytotoxicity and 5-FU mediated radiosensitization with selumetinib treatment was accompanied by an increase in mitotic catastrophe and apoptosis, and reductions in Stat3 phosphorylation and survivin expression. In vivo, an additive growth delay was observed with 5-FU + selumetinib + 3Gy versus 5-FU + 3Gy and selumetinib alone.

Conclusion: These data suggest that selumetinib can be used with 5-FU to augment radiation response.

Introduction

One of the hallmarks of cancer cells is the upregulation of cellular pathways that provide survival advantages by promoting proliferation and/or decreasing cell death (1). One such pathway is the Ras/Raf/mitogen activated protein kinase (MAPK)/extracellular signal-regulated kinase (ERK) pathway, which is involved in cell proliferation, differentiation, apoptosis, and survival. Inhibition of the Ras/MAPK pathway has been explored as an anticancer therapy. Selumetinib (AZD6244, ARRY-142886), a selective inhibitor of MEK1/2, has been shown to have single-agent efficacy in a variety of human tumor cell lines, with greater single agent efficacy observed in B Raf and KRas mutant cell lines (2).

Activation of the Ras/MAPK pathway has been implicated in resistance to ionizing radiation (3, 4) and cytotoxic chemotherapy (5, 6). Others and we have previously shown that inhibition of signaling via the Ras/MAPK pathway enhances sensitivity to radiation (7–9). Inhibition of the Ras/MAPK pathway has also been exploited as a means to sensitize tumors cells to cytotoxic chemotherapy (5, 6).

Gastrointestinal cancers frequently exhibit activation of the Ras/MAPK pathway via activating mutations in RAS (10) and/or RAF (11–14). The presence of either a Ras or Raf mutation is associated with an inferior prognosis compared with nonmutated tumors (14–16). Concurrent radiotherapy and radiation sensitizing 5-fluorouracil (5-FU) based chemotherapy is a common treatment strategy for gastrointestinal malignancies. Despite aggressive chemoradiotherapy, local failure remains a troubling clinical problem that requires development of more effective regimens.
The purpose of the current study was to evaluate if inhibition of MEK1/2 could enhance 5-FU mediated radiosensitization. We describe enhancement of radiation response with 5-FU and selumetinib compared with either agent alone. We also show an enhancement of the cytotoxic and antiproliferative activity of 5-FU in the setting of MEK1/2 inhibition regardless of treatment sequencing. The enhancement of 5-FU cytotoxicity and 5-FU mediated radiation sensitization with selumetinib treatment was accompanied by an increase in mitotic catastrophe and apoptosis, a reduction in stat3 phosphorylation, and a reduction in survivin expression. These data suggest that concurrent treatment of selumetinib with 5-FU may be used in patients with gastrointestinal malignancies to augment radiation response.

Materials and Methods

Cells lines and treatments

The colorectal carcinoma cell lines, HT29 (ATCC # HTB-38) and HCT116 (ATCC # CCL-247), and pancreatic carcinoma cell line MiaPaCa-2 (ATCC # CRL-1420) were maintained in RPMI 1640 medium (ATCC) containing 10% FBS at 37°C in a humidified atmosphere with 5% CO₂. All cell lines were passed for fewer than 6 months after resuscitation. Selumetinib (supplied by Astra Zeneca) was reconstituted in dimethyl sulfoxide (DMSO) and stored at −20°C. 5-Fluorouracil (5-FU; Teva Parenteral Medicines) was diluted in PBS (Invitrogen) immediately prior to each experiment. The final concentration of 5-FU used was 15 μmol/L in all experiments.

Clonogenic survival assay

Cells were trypsinized to form single cell suspensions and plated at appropriate concentrations in triplicate in 6-well plates. Six hours after plating, 5-FU or vehicle control (PBS) was added. Sixteen hours after the addition of 5-FU, selumetinib (final concentration 250 nmol/L for HCT116 and MiaPaCa-2, 100 nmol/L for HT29), or DMSO (vehicle) was added. Cells were irradiated 2 hours after the addition of selumetinib using a Pantak X-ray unit at a dose rate of 1.55 Gy/min. 5-FU was removed from the media immediately following irradiation and incubation was continued with selumetinib. Ten to 12 days after irradiation, cells were fixed, stained with crystal violet, and the number of colonies containing at least 50 cells was determined. Surviving fractions for each treatment were determined by normalizing the average plating efficiency for each dose to the plating efficiency at 0 Gy. Assays were carried out in triplicate. Dose modification factors (DMFs) were calculated by taking the ratios of the radiation dose that resulted in 10% survival (control radiation dose divided by the drug-treated radiation dose). DMF values greater than 1.0 indicate enhancement of radiosensitivity.

Western blotting

Cell lysates were prepared using RIPA buffer (Pierce) containing phosphatase (Sigma-Aldrich) and protease (Roche) inhibitors and protein concentration was determined using a DC protein assay kit (Bio-Rad). Equal amounts of protein were subjected electrophoresis carried out under reducing conditions and gels were blotted to nitrocellulose membranes. All primary antibodies used were purchased from Cell Signaling (Danvers) with the exception of antiphospho γH2AX and antiactin (Millipore). All western blotting experiments were conducted in duplicate.

Immunocytochemistry for γH2AX

Cells were fixed in 2% paraformaldehyde for 15 minutes at room temperature and permeabilized with 1% Triton X-100 for 10 minutes on ice. Slides were incubated in anti-phospho γH2AX (Millipore) for 1 hour at 4°C, an Alexa Fluor-conjugated secondary antibody (Invitrogen) for 1 hour at room temperature, and nuclei were counterstained with DAPI (Sigma-Aldrich). Slides were viewed using a Leica microscope with fluorescence capability and images were captured using a Q Imaging camera. The percentage of cells containing ≥50 foci was determined in 150 cells for each condition. Experiments were carried out in triplicate.

Evaluation of mitotic catastrophe

The presence of fragmented nuclei was used as the criteria for defining cells undergoing mitotic catastrophe. To visualize nuclear fragmentation cells were fixed with 2% paraformaldehyde for 15 minutes at room temperature, permeabilized with 0.5% Triton X-100 for 1 hour on ice, and stained with anti-α-tubulin antibody (Millipore) followed by staining with an Alexa Fluor-conjugated secondary antibody (Invitrogen), each for 1 hour at room temperature. Nuclei were counterstained with DAPI. Cells were imaged with a Leica microscope with fluorescence capability. Nuclear fragmentation was defined as
the presence of more than two distinct nuclear lobes within a single cell. The percentage of cells with nuclear fragmentation was determined in 150 randomly selected cells in each of 2 separate experiments.

**Flow cytometry**

For cell cycle analysis, cells were trypsinized, washed with PBS, fixed with 100% ethanol, and stored at −20°C. Fixed cells were washed with 0.5% BSA and incubated in a solution containing 0.1% Triton X-100, 0.2 mg/mL RNase A, and 20 mg/mL propidium iodide. DNA content was determined from 2 individual experiments using FACS Calibur cytometry (BD Biosciences) and FlowJo software (Tree Star, Inc.).

For apoptosis analysis, a modified protocol from the ApopNexin FITC Apoptosis Detection Kit (Millipore) was used. Briefly, media was aspirated and collected with attached cells. Attached cells were trypsinized, collected and washed with ice-cold PBS. Cells were resuspended in binding buffer and incubated with ApopNexin FITC and propidium iodide at room temperature in the dark. Cells positive for Annexin V were determined from 2 individual experiments using FACS Calibur cytometry (BD Biosciences) and analyzed using FlowJo software (Tree Star, Inc.).

**Proliferation assay**

Cells were plated in 96-well plates and treated with 5-FU and selumetinib at the time-points and durations indicated. Following the indicated treatment, media were replaced to remove 5-FU. The number of viable cells at 72 hours after plating was determined using the CellTiter 96 Non-radioactive Cell Proliferation Assay according to the manufacturer's protocol (Promega). Briefly, 72 hours after plating, cells were treated with 3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT) for 4 hours at 37°C before addition of stop solution. After 1 hour, changes in absorbance were read at 570 nm in a plate reader and expressed as a percent of control absorbance. All conditions were assayed in triplicate and experiments were repeated 3 times.

**In vivo tumor model**

Six to eight week-old female nude mice (Freddie Labs) were caged in groups of five or less, and fed a diet of animal chow and water ad libitum. HCT116 tumor cells (1 × 10⁶ cells) were injected subcutaneously into the right hind leg. When tumors grew to a mean volume of 172 mm³, the mice were randomized to treatment groups (8 mice per group). At time 0, mice receiving 5-FU were given 100 mg/kg via intraperitoneal injection whereas all other mice received an injection of PBS. Two hours later, mice receiving selumetinib were given a single oral dose of selumetinib at 50 mg/kg whereas all other mice received an oral dose of DMSO. Six hours after 5-FU and 4 hours after selumetinib, mice received a dose of 3 Gy to the tumor. Irradiation was carried out using a Therapax DXT300 X-ray irradiator (Precision X-ray Inc.) using 2.0 mm Al filtration (300 kVp) at a dose rate of 1.9 Gy/minute with animals restrained in a custom jig that allows exposure of the tumor bearing leg with shielding of the rest of the body. To obtain a tumor growth curve, perpendicular diameter measurements of each tumor were measured every 3 days with digital calipers, and volumes were calculated using the formula (L × W × W)/2. Tumors were followed individually until they measured greater than 600 mm³. Tumors that failed to regrow were followed for 90 days after treatment. Specific tumor growth delay was calculated for each individual animal. The mean growth delay for each treatment group was calculated as the number of days for the mean of the treated tumors to grow to 600 mm³ minus the number of days for the mean of the control group to reach the same size. Each animal study was conducted in accordance with the principles and procedures outlined in the NIH Guide for the Care and Use of Animals.

**Statistics**

All data were analyzed with SAS using Proc GLM with a significance level of P < 0.05. Duncan’s multiple range test was used to determine significant differences between means.

**Results**

To determine if selumetinib could enhance the radiation sensitization observed with 5-fluorouracil, we carried out clonogenic survival assays with three tumor cell lines. Doses and timing of 5-FU were chosen based on published data (17, 18) and preliminary work carried out in our laboratory confirming radiation sensitization. Clonogenic survival in all 3 cell lines was significantly reduced with 5-FU, selumetinib, and combined 5-FU+ selumetinib pre-IR treatment. Clonogenic survival after pre-IR treatment with 5-FU+ selumetinib was reduced beyond that observed with either agent alone with DMFs of 1.78, 1.52, and 1.3 for HT29, HCT116, and MiaPaCa-2, respectively (Fig. 1). Dose-dependency of the selumetinib and 5-FU+ selumetinib combination effect was observed with a less dramatic enhancement of radiosensitization in HCT116 and MiaPaCa-2 cells treated with a combination of a lower dose of selumetinib (100 μmol/L) and 5-FU (data not shown). Toxicity was calculated by subtracting the plating efficiency for each treatment in the unirradiated condition from one. Toxicity was greatest with 5-FU+ selumetinib compared with selumetinib or 5-FU in all cell lines.

In an effort to better understand the cellular mechanisms underlying enhancement radiation sensitization with the combined treatment of 5-FU+ selumetinib, we focused on the HCT116 cell line. To confirm that target inhibition with selumetinib was present in the setting of 5-FU, IR, or the combination, phosphorylation of ERK1/2 was determined in each setting. Western blotting analysis confirmed basal ERK phosphorylation, consistent with the known status as Ras mutants. Selumetinib treatment inhibited basal phosphorylation of ERK1/2.
Treatment with selumetinib was sufficient to inhibit ERK phosphorylation after exposure to 5-FU, IR, or the combination of 5-FU and IR (Fig. 2).

Antagonism of the cytotoxic and cytostatic effects of 5-FU is a major concern when combining 5-FU treatment with agents known to alter cell-cycle distribution. The cytotoxic effects of 5-FU are known to be cell-cycle dependent, and selumetinib is known to redistribute cells into G0 and G1 phases of the cell cycle (19, 20). Theoretically, treatment with selumetinib could reduce the cycling fraction and result in antagonism of 5-FU. Therefore, we evaluated if sequencing of 5-FU in relation to selumetinib would alter the antiproliferative effects of either agent. To determine the effects of altering treatment order and duration, three treatment sequences were evaluated, which altered the timing of 5-FU treatment in

Figure 1. The effects of selumetinib and 5-FU on tumor cell radiosensitivity. Cell lines HT29 (A), HCT116 (B), and MiaPaCa-2 (C) were exposed to 15 μmol/L 5-FU (or vehicle) for 18 hours and selumetinib (or vehicle) for 2 hours and irradiated with graded doses of X-rays. Colony forming efficiency was determined 10 to 12 days later and survival curves generated after normalizing for cell killing by selumetinib, 5-FU or selumetinib + 5FU in the absence of IR. The data represent the mean of three independent experiments. (Points, mean; bars, standard error; DMF, dose modifying factor; toxicity, mean plating efficiency at 0 Gy.)
cell-cycle distribution is not responsible for the increased sensitivity to radiation.

DNA damage repair is an important component of 5-FU and radiation-induced cytotoxicity. To evaluate the induction and repair of DNA double-strand breaks, we counted phosphorylated histone H2AX (γH2AX) foci. The percent of cells with greater than 50 foci was calculated at 1, 6, and 24 hours after cells were treated with 5-FU and selumetinib as in the clonogenic assays and irradiated to 4 Gy. In vehicle and selumetinib treated cells, irradiation induced a significant increase \((P < 0.05)\) in the number of γH2AX foci at 1 hour, which progressively declined to 24 hours (Fig. 3). Exposure to 5-FU, selumetinib, or 5-FU+ selumetinib followed by 4 Gy resulted in a number of γH2AX foci not significantly higher to that observed with 4 Gy alone at 1 hour suggesting that these treatments do not impact immediate DNA damage after IR. At 24 hours after radiation, the number of cells with more than 50 γH2AX foci per cell was higher in the 5-FU+selumetinib

**Figure 2.** The effects of Selumetinib on ERK1/2 phosphorylation after exposure to IR and 5-FU. HCT116 cells were treated with 15 μmol/L 5-FU (or vehicle) for 18 hours and 250 nmol/L selumetinib (or vehicle) for 2 hours prior to irradiation with 4 Gy. Lysates were collected 2 hours after cells were irradiated. Blots are representative of at least 2 individual experiments. 

**Figure 3.** The effects of 5-FU and selumetinib on DNA double strand break repair. HCT116 cells growing in chamber slides were treated with 15 μmol/L 5-FU (or vehicle) for 18 hours and 250 nmol/L selumetinib (or vehicle) for 2 hours prior to irradiation with 4 Gy. Following irradiation, cells were washed with PBS, and media containing 250 nmol/L selumetinib (or vehicle) was added. A, at the indicated time points, cells were fixed and subjected to immunocytochemistry for γH2AX (γH2AX labeled with red, nuclei with blue). [Columns, mean from 3 independent experiments; bars, standard deviation; *, \(P < 0.05\) (selumetinib + 5-FU + 4 Gy vs. vehicle + 4 Gy and selumetinib + 4 Gy).]

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treated cells compared with 5-FU, vehicle, or selumetinib treated cells, suggesting that the combination of 5-FU and selumetinib resulted in inhibition of DNA repair (Fig. 3; \( P < 0.05 \)).

Mitotic catastrophe is a common method of cell death after IR. To determine if treatment with 5-FU and selumetinib together enhanced mitotic catastrophe after IR compared with the individual treatments, we determined the percentage of cells that contained more than 2 distinct nuclear bodies at 24, 48, and 72 hours after IR (21). Within 48 hours after radiation, a significantly greater number of cells were scored as undergoing mitotic catastrophe in the 5-FU+selumetinib treated cells as compared to either selumetinib or 5-FU treated cells at the same time-point (Fig. 4A), an effect which persisted at 72 hours. As supplemental evidence, we determined DNA content using flow cytometry. A significant increase in cells with >4N DNA content was observed in HCT116 cells (Supplementary Fig. 2). A significant increase in mitotic catastrophe therefore may be a mechanism by which treatment with selumetinib enhances 5-FU radiosensitization.

To determine if apoptotic cell death was also an important component of cell death after treatment with 5-FU and/or selumetinib after irradiation, we evaluated the percentage of apoptotic cells after treatment with 5-FU, selumetinib, or the combination after exposure to IR. A significant increase (\( P < 0.05 \)) in apoptotic cells was found in irradiated cells after treatment with 5-FU+selumetinib compared with single agent or vehicle treatments (Fig. 4B).

In an attempt to identify a molecular explanation for the increase in mitotic catastrophe and apoptosis observed in cells treated with 5-FU in combination with selumetinib, we determined the protein expression of survivin, a known inhibitor of apoptosis that plays a role in mitotic progression, and one of survivin’s transcriptional regulators, Stat3, by western blotting analysis. Survivin is a known downstream target of the MAPK/ERK pathway (22). A decrease in both phosphorylated Stat3 and survivin protein expression and an increase in cleaved caspase 3 and cleaved PARP were found in cells treated with the combination of 5-FU+selumetinib as compared with radiation, 5-FU, or selumetinib alone (Fig. 5A), suggesting that the enhancement of radiation effect observed with selumetinib and 5-FU compared with either agent individually may be related to the inhibition of downstream mediators of apoptosis and mitotic catastrophe after IR.

Survivin expression is known to be regulated by the cell cycle, with dominant expression observed in G2 and M phases (23). To confirm that cell-cycle redistribution was not responsible for the observed reduction in survivin expression with selumetinib treatment, we evaluated the cell-cycle distribution of cells treated with selumetinib, 5-FU, and IR. At the time-point in which reduced survivin expression was observed with selumetinib +5-FU (24 hours after IR), there was no significant difference in the percentage of cells in the G2 and M phases of the cell cycle (Fig. 5B).

To confirm that the enhancement of radiation sensitization observed in vitro could be translated into an in vivo tumor model, a tumor growth delay assay using HCT116 cells grown subcutaneously (sc) in the hind leg of mice was used. Athymic nude mice bearing sc xenografts (172 mm3) were randomized into four groups: vehicle; selumetinib only; 3 Gy + 5-FU; and selumetinib +5-FU + 3 Gy. Selumetinib was delivered as a single 50 mg/kg dose by oral gavage 4 hours prior to IR. 5-FU was delivered as a 100 mg/kg IP dose 6 hours prior to IR. Treatment was on the day of randomization. The growth rates for the HCT 116 tumors exposed to each treatment are shown in Fig. 6. For each group, the time for tumors to triple in size (from volume at the time of treatment) was calculated using the

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**Figure 4.** The effects of selumetinib on the mechanism of cell death after exposure to 5-FU and IR. A, HCT116 cells growing in chamber slides were exposed to 15 \( \mu \)mol/L 5-FU (or vehicle) for 18 hours and 250 nmol/L selumetinib (or vehicle) for 2 hours prior to irradiation (4 Gy). Following irradiation, cells were washed with PBS, and media containing 250 nmol/L selumetinib (or vehicle) was added. Cells were fixed at the time points indicated for immunocytochemical analysis of mitotic catastrophe. Nuclear fragmentation was evaluated in 150 cells per experiment. B, HCT 116 cells were treated with 5-FU (or vehicle) for 18 hours and selumetinib (or vehicle) for 2 hours prior to irradiation (4 Gy) and harvested at the specified times. Treated cell samples were added to a 150 \( \mu \)L staining solution (Cytofix/Cytoperm) containing 135 \( \mu \)L 1× apoptosis buffer, 10 \( \mu \)L Annexin V-PE, and 5 \( \mu \)L of 7-AAD. Samples (2,000 cells per sample) were evaluated by flow cytometry. (Columns, mean; bars, standard deviation; *, \( P < 0.05 \) as compared with other treatments at the specified time-point.)
tumor volumes from the individual mice in each group (mean ± SE).

For the HCT116 xenograft model, the time required for tumors to triple in volume from the initiation of treatment increased from 7.1 ± 0.5 days for vehicle treated mice to 8.8 ± 0.6 days for selumetinib (50 mg/kg) treated mice. Treatment with 3 Gy + 5-FU increased the time to triple in volume to 11.7 ± 1.0 days. However, in mice that received the combination of 3 Gy + 5-FU + selumetinib, the time for tumors to triple increased to 22.9 ± 10.4 days. The large SEM value for the 3 Gy + 5-FU + selumetinib treatment group was due to a tumor cure (no regrowth at 90 days). The absolute growth delays (the time in days for tumors in treated mice to triple in volume minus the time in days for tumors to reach the same size in vehicle treated mice) were 1.7 days for selumetinib alone, 4.6 days for 3 Gy + 5-FU, and 13.8 days for 3 Gy + 5-FU + selumetinib. Thus, the combined treatment was more than the sum of the growth delays caused by individual treatments.

To obtain a dose enhancement factor comparing the tumor radiation response in the setting of 5-FU in mice with and without selumetinib treatment, the normalized tumor growth delays were calculated, which accounts for the contribution of selumetinib to tumor growth delay induced by the combination treatment. Normalized tumor growth delay was defined as the time in days for tumors to triple in volume in mice exposed to the combined modality minus the time in days for tumors to triple in size in mice treated with selumetinib only. The dose enhancement factor, obtained by dividing the normalized tumor growth delay in mice treated with 3 Gy + 5-FU + selumetinib by the absolute growth delay in mice treated with 3 Gy + 5-FU, was 3.4 for the addition of selumetinib.

Collectively, these data confirm a lack of antagonism with the addition of selumetinib to 5-FU and IR and indicate that selumetinib may provide at least an additive enhancement of radiation response when combined with 5-FU and IR. These effects correlate to an increase in DNA double strand breaks and an increase in mitotic catastrophe after irradiation in selumetinib treated cells compared to cells treated with irradiation alone.

**Discussion**

Selumetinib is a selective MEK1/2 inhibitor that is currently being tested in combination with a variety of other agents in Phase I and II trials. Selumetinib has broad preclinical activity with increased single agent efficacy in cancer cell lines with *Braf* or *Kras* mutations (24). Selumetinib has previously been shown, by our lab and others,
to enhance the radiation response of tumor lines both in vitro and in vivo (7, 8).

In the present study, we evaluated the radiosensitizing effects of selumetinib when combined with 5-FU and irradiation in three gastrointestinal cell lines. This evaluation is critical to the clinical translation of selumetinib as a radiation sensitizer in the setting of combined therapy with 5-FU and IR, the current standard therapy for a wide range of gastrointestinal malignancies. In mammalian cells, 5-FU is converted into metabolites that either damage DNA directly by incorporation into nucleic acids or indirectly by inhibition of thymidylate synthase, thus causing uridine incorporation into DNA due to a nucleotide pool imbalance [reviewed in (25, 26)].

We found enhanced radiosensitization when cells were treated with 5-FU + selumetinib as compared either agent alone with IR. Evaluation of ERK phosphorylation in each setting confirmed target inhibition in the presence of 5-FU and irradiation with selumetinib treatment. These findings were confirmed in HCT116 xenografts in which the addition of selumetinib to 5-FU and IR led to augmentation of radiation response.

An increase in mitotic catastrophe and apoptosis were identified as two mechanisms of cell-death correlating with enhanced radiosensitization. We identified a greater persistence of DNA double strand breaks in the setting of treatment with 5-FU and selumetinib with IR compared with IR alone. Consistent with the reduction in DNA repair, we found an increase in the proportion of cells undergoing mitotic catastrophe after exposure to 5-FU and selumetinib with IR compared with either agent alone with IR.

Both 5-FU (27) and selumetinib (7) have been shown separately to induce mitotic catastrophe. We found a synergistic induction in mitotic catastrophe when 5-FU, selumetinib, and IR were combined that was preceded by a decrease in survivin expression. Decreased survivin expression was accompanied by decreased expression of one of its transcriptional regulators, phosphorylated Stat3. As Stat3 is a known to function downstream of phosphorylated ERK (28), this provides one potential mechanism to explain the increase in apoptosis and mitotic catastrophe observed in irradiated cells after exposure to 5-FU and selumetinib.

Survivin is known to play an important role in several aspects of cell division such as sister chromatid segregation, microtubule assembly/stabilization, and regulation of mitotic progression (23, 29). Importantly, mitosis but not cytokinesis occurs in survivin-depleted cells (29). Combined with the finding that survivin expression affects DNA repair (30–33), these results suggest that decreased survivin expression may lead to disordered mitosis and mitotic catastrophe through a number of mechanisms.

Interesting in light of the current results, previous studies have indicated that survivin levels affect the response of some cells, including colorectal and pancreatic cancer cells, to radiation therapy (30, 31, 34) and treatment with 5-FU (35–38). Survivin was previously identified as an inhibitor of apoptosis and it has been shown that overexpression of survivin leads to an inhibition of apoptotic cell death [reviewed in (39)]. The reverse, that downregulation of survivin leads to an increase in apoptosis, has also been shown (30, 33, 35). Therefore, the increase in apoptotic cell death observed after treatment with selumetinib + 5-FU + IR could also be attributed to survivin depletion.

Our current results indicate that in the absence of radiation, the combination of 5-FU and selumetinib resulted in a decrease in tumor-cell proliferation. Because treatment with selumetinib may have effects on cell cycle (19, 20) and the cytotoxicity of 5-FU depends on progression through S-phase (40), reviewed in (41), we wanted to ensure that coupling treatment with 5-FU and selumetinib did not impair the efficacy of 5-FU in the absence of radiation. This information is critical when considering that subclinical distant disease will not be targeted by irradiation. Our results indicate that the addition of selumetinib to 5-FU results in enhanced antiproliferative and cytotoxic effects compared with that observed with selumetinib or 5-FU alone, regardless of treatment sequencing. Even in the setting of prolonged exposure to selumetinib prior to treatment with 5-FU, there was no evidence of antagonism between the two agents. The data from proliferation experiments correlate to the observed reduction in plating efficiency observed with the combination of 5-FU and selumetinib compared to either agent alone in clonogenic assays. Our data suggesting an additive effect of 5-FU and selumetinib are consistent with prior studies suggesting that ERK phosphorylation is a resistance factor to 5-FU mediated cytotoxicity (5).

This is the first study, to our knowledge, that examines the effects of combining MEK1/2 inhibition with 5-FU and IR. In the absence of IR, we found that selumetinib enhanced in the cytotoxic and antiproliferative effects of 5-FU, regardless of sequencing. When combined with IR, treatment with 5-FU + selumetinib enhanced radiosensitization. The enhancement of 5-FU mediated radiosensitization with selumetinib was accompanied by increases in apoptosis and mitotic catastrophe. We identified persistence in DNA double strand breaks and decrease in survivin expression as a potential mechanism to explain the increase in apoptosis and mitotic catastrophe. These data add to the growing evidence showing that targeting the Ras/MAPK pathway enhances efficacy of chemotherapeutic agents and indicate that inhibition of MEK1/2 may provide a means to enhance 5-FU mediated radiation sensitization.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Grant Support

This research was supported by the Intramural Research Program of the National Institutes of Health, National Cancer Institute.

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Received February 8, 2011; revised April 11, 2011; accepted May 18, 2011; published OnlineFirst June 20, 2011.
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Clin Cancer Res 2011;17:5038-5047. Published OnlineFirst June 20, 2011.

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