

## MEK1/2 Inhibitors AS703026 and AZD6244 May Be Potential Therapies for *KRAS* Mutated Colorectal Cancer That Is Resistant to EGFR Monoclonal Antibody Therapy

Juyong Yoon, Kyoung-Hwa Koo, and Kang-Yell Choi

### Abstract

Epidermal growth factor receptor (EGFR) monoclonal antibodies (mAb) are used widely to treat metastatic colorectal cancer (mCRC) patients, but it is now clear that patients harboring *K-ras* mutation are resistant to EGFR mAbs such as cetuximab (Erbix) and panitumumab (Vectibix). For this reason, current recommendations for patient care involve diagnosing the *K-ras* mutational status of patients prior to EGFR mAb therapy. In this study, we investigated the ability of two MEK inhibitors currently in clinical trials, AS703026 and AZD6244, to address the challenge posed by the resistance of *K-ras* mutated colorectal cancers to EGFR mAb. AS703026 and AZD6244 were tested in various cell-based assays and tumor xenograft studies, focusing on isogenic human colorectal tumor cell lines that expressed only WT or mutant *K-Ras* (D-WT or D-MUT). The EGFR mAb cetuximab inhibited the Ras-ERK pathway and proliferation of D-WT cells *in vitro* and *in vivo*, but it did not inhibit proliferation of D-MUT cells in either setting. In contrast, AS703026 and AZD6244 effectively inhibited the growth of D-MUT cells *in vitro* and *in vivo* by specific inhibition of the key MEK downstream target kinase ERK. Inhibition of MEK by AS703026 or AZD6244 also suppressed cetuximab-resistant colorectal cancer cells attributed to *K-ras* mutation both *in vitro* and *in vivo*. Our findings offer proof-of-concept for the use of MEK inhibitors as an effective therapy in *K-ras* mutated CRC. *Cancer Res*; 71(2); 445–53. ©2010 AACR.

### Introduction

Colorectal cancer is a commonly diagnosed malignancy and a major cause of cancer-related death (1, 2). During the past decade, the median overall survival time for patients with metastatic colorectal cancer (mCRC) has increased from 12 to 21 months, primarily due to chemotherapy with oxaliplatin, irinotecan, and 5-fluorouracil (3). Newly developed molecular targeted therapies using monoclonal antibodies (mAbs), such as cetuximab (Erbix), panitumumab (Vectibix), trastuzumab (Herceptin), and Bevacizumab (Avastin) have provided clinically meaningful benefits in treating colorectal cancer (4–6). Most novel therapies have developed by targeting the vascular endothelial growth factor (VEGF) and epidermal growth factor (EGF) signaling involving angiogenesis and proliferation of cancer cells.

As many human cancers, including colorectal cancer, involve abnormal expression of EGF receptor (EGFR), which is implicated in the development and prognosis of malignancy, EGFR is a rational molecular target for cancer treatment (7).

However, the benefit from anti-EGFR mAb therapy using cetuximab and panitumumab is limited to only a small portion (8~23%) of patients. The patients with mCRC bearing *K-ras* activating mutation are resistant to EGFR mAb therapy (8–12). In July 2009, the FDA recommended that the *K-Ras* gene mutational status of mCRC patients be screened prior to treatment with EGFR mAb to avoid wasting time and disbursement (13).

Most *K-ras* mutations occur in the mid-adenoma stages in the colorectal tumorigenesis (14). Ras activation stimulates cell proliferation via the Raf-MEK-ERK and PI3 kinase-Akt pathways, which involves development of carcinoma (15–17). Cetuximab is a monoclonal antibody targeting EGFR, and its binding to the extracellular domain of EGFR prevents ligand binding and inhibits signaling cascades, such as the Ras-Raf-MEK-ERK and PIK3CA-Akt pathways (18). Considering the epistasis of the Ras-Raf-MEK-ERK cascade, we hypothesized that MEK inhibition may overcome cetuximab resistance attributed to *K-ras* mutations in some colorectal cancers.

To investigate the sensitivity of cetuximab resistance dependent on *K-ras* mutation in cells and tumors, we used isogenic DLD-1 colorectal cancer cell lines (D-WT and D-MUT) in which wild-type (WT) and mutant *K-Ras* alleles have been inactivated by homologous recombination (19). These cell lines share the same genetic background with the exception of 1 base pair of codon 13 in the *K-Ras* gene. Considering intact DLD-1 cells that are heterozygous for *K-Ras*, this paired colorectal cell line provides an ideal system to distinguish the responsiveness of a drug against *K-ras* mutation. In this study,

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we address the effect of *K-ras* mutation on the responsiveness of colorectal cancer cells to cetuximab using D-WT and D-MUT cells and tumors. We further evaluated the effect of MEK inhibition on the responsiveness of the D-WT and D-MUT cell lines using 2 MEK1/2 inhibitors, AS703026 and AZD6244, which are currently undergoing clinical trial-phase I and phase II, respectively (20, 21). We observed that the MEK inhibitors are effective in inhibiting tumor cell growth on the D-MUT cells harboring a *K-ras* mutation both *in vitro* and *in vivo*, in contrast to cetuximab. The MEK inhibitors reduced activities of the ATF2 transcription factors which were also not affected by cetuximab in *K-ras* mutated tumors. This study, based on the recent clinical observations related to cetuximab resistance (8–11, 22), is a pioneering study to investigate the responsiveness of an EGFR mAb to a *K-ras* mutation using isogenic colorectal cancer cell lines and their xenograft models.

## Materials and Methods

### Reagents

The antibodies used in this study were anti- $\beta$ -catenin (BD Bioscience); Pan-Ras (Upstate Biotechnology);  $\alpha$ -tubulin (Calbiochem); p-ERK, p-ATF2 (T71) (Cell Signaling Technology); p-Akt, PCNA,  $\beta$ -actin (Santa Cruz Biotechnology); anti-rabbit AlexaFluor 488 and anti-mouse AlexaFluor 555 (Invitrogen). Bromodeoxyuridine (5-bromo-2-deoxyuridine, BrdU) was purchased from DAKO. Cetuximab (Erbix) and AS703026 were provided by Merck KGaA. AZD6244 was obtained from OTAVA.

### Cell culture

Human colorectal cancer cell lines with either wild-type (D-WT) or mutated *K-Ras* (D-MUT) were kindly provided by Dr. Bert Vogelstein (Johns Hopkins Oncology Center, Baltimore, MD) in 2009. These cell lines are derived from DLD-1 human colon cancer cell in which the endogenous wild-type or mutant alleles had been inactivated through targeted homologous recombination (19). D-WT and D-MUT cells were grown in RPMI 1640 (Gibco) containing 10% fetal bovine serum (FBS), 100 U/mL penicillin, and 100  $\mu$ g/mL of streptomycin at 37°C. Cells were checked by morphology and were tested to be *Mycoplasma*-free using MycoFluor Mycoplasma Detection Kit (Invitrogen) within the last 6 months. D-WT and D-MUT cells were authenticated by mutational analysis of *K-Ras*, as described below.

### Mutational analysis of *K-ras*

For mutational analysis of *K-ras*, total genomic DNA was extracted from D-WT and D-MUT cells using the QIAamp DNA Mini kit (QIAGEN). DNA (50 ng) were amplified in a 20  $\mu$ L reaction mixture containing 2  $\mu$ L 10x buffer (Roche), 1.7 to 2.5 mmol/L MgCl<sub>2</sub>, 0.3  $\mu$ mol/L each primer pair (codon 12, 13, F: 5'-TTATGTGTGACATGTTCTAAT-3', R: 5'-AGAATGGTCTG-CACCAGTAA-3' codon 61, F: 5'-TCAAGTCCTTGGCCAT-TTT-3', R: 5'-TGCATGGCATTAGCAAAGAC-3'), 250  $\mu$ mol/L deoxynucleotide triphosphates, and 2.5 units of DNA polymerase (Roche Diagnostics). Amplification was carried out using a

5-minute initial denaturation at 94°C, followed by 30 cycles of 1 minute at 94°C, 1 minute at 55°C, and 1 minute at 72°C, and a 10-minute final extension at 72°C. Polymerase chain reaction (PCR) products were separated on a 2% agarose gel and gel-purified with a QIAGEN gel extraction kit (QIAGEN) before being subjected to DNA sequencing analysis.

### MTT assay and BrdU incorporation

Cells were plated at a density of  $4 \times 10^4$  cells per 24 well and treated with MEK inhibitor, AS703026 or AZD6244 with/without cetuximab for 72 hours. MTT reagent [3-(4,5-Dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; AMRESCO, Solon, OH] was diluted in RPMI 1640 at a concentration of 0.25 mg/mL. Cells were incubated for 3 hours at 37°C. Media was removed and insoluble purple formazan was solubilized with 500  $\mu$ L DMSO for 30 minutes. The absorbance of formazan product was determined at 500 nm. For *In vitro* BrdU labeling, cells were treated with 20  $\mu$ mol/L BrdU for 4 hours. Cell were fixed with 4% paraformaldehyde for 30 minutes and treated with 0.1% Triton X-100 for 15 minutes. Then, cells were blocked by 5% bovine serum albumin (BSA) and 1% normal goat serum (NGS) in PBS for 30 minutes and incubated with anti-BrdU antibody (1:200), overnight at 4°C, followed by incubation with anti-mouse Alexa Flour 555 secondary antibody, and counterstained by DAPI (Boehringer Mannheim), and then mounted in Gel/Mount media (Biomedica Corporation). Visualization of fluorescence signal was done using confocal microscopy (LSM510, Carl-Zeiss) at excitation wavelengths of 488 nm (Alexa Fluor 488), 543 nm (Alexa Fluor 555), and 405nm (DAPI). Each experiment was repeated 3 times. Data are given as mean  $\pm$  SD.

### Foci formation assay

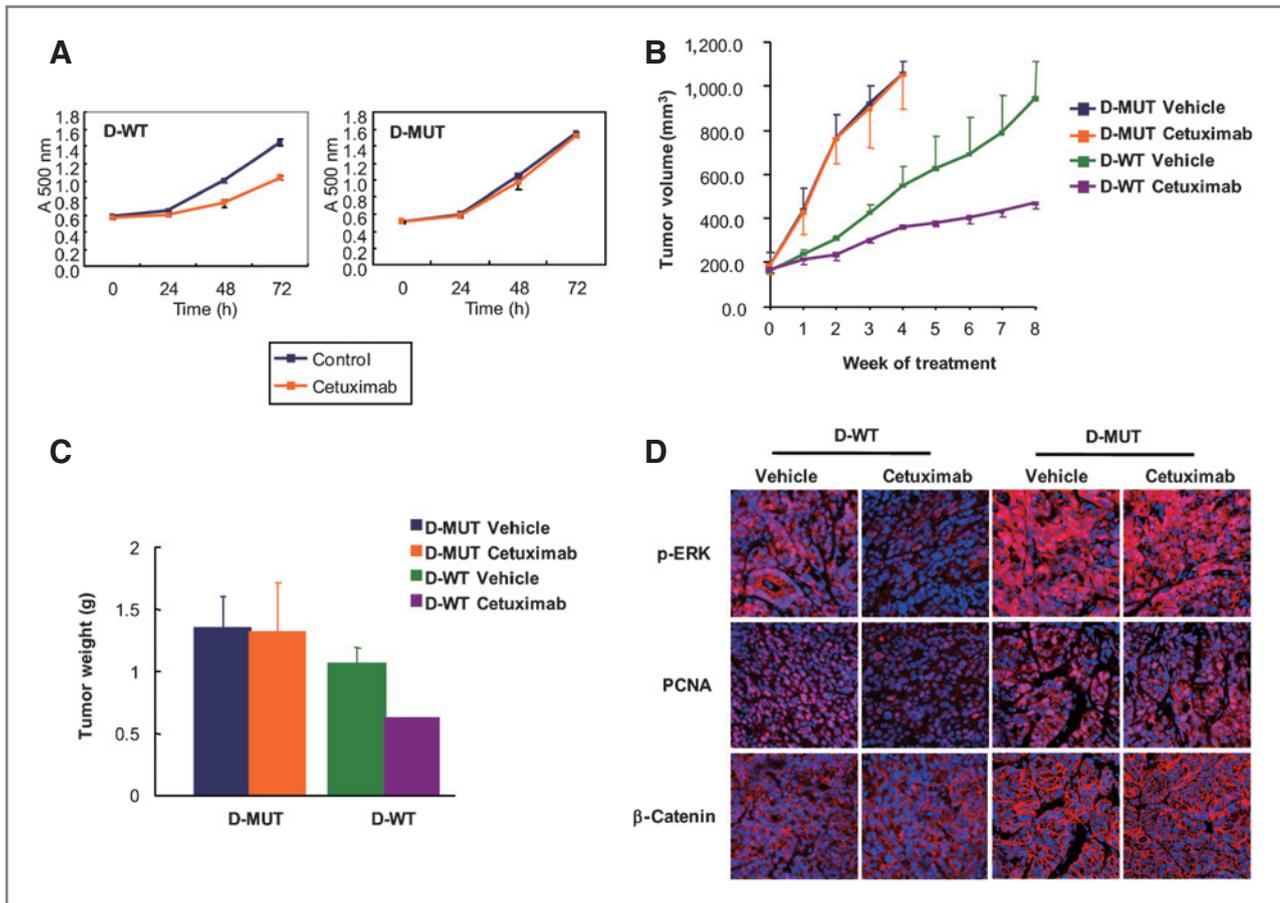
D-WT and D-MUT cells were seeded at a density of 500 cells in each well of 6-well plates. The cells were treated with MEK inhibitor, AS703026 or AZD6244 with/without cetuximab at every 3 days for 7 (D-MUT) or 14 (D-WT) days. Media was changed every 3 days. After 7 (D-MUT) or 14 (D-WT) days, cells were stained with 0.5% crystal violet in 20% ethanol.

### Ras activation assay and immunoblotting

Cells were lysed with 2% Triton X-100, 100 mmol/L HEPES (pH 7.5), 200 mmol/L NaCl, 10 mmol/L MgCl<sub>2</sub>, 2 mmol/L sodium orthovanadate, mammalian cell protease inhibitor mixture, and cleared by centrifugation at 14,000 $\times$ g for 5 minutes at 4°C. Aliquots of lysates were to allow quantification of total Pan-Ras,  $\alpha$ -tubulin, p-ERK, p-Akt, ERK by immunoblotting. The remainder of cell lysates was incubated with bead coated with fusion protein (GST-Raf1-RBD; Upstate Biotechnology, Inc.) at 4°C for 1 hour. Beads were washed 3 times with cold lysis buffer, and bounded protein was eluted with 4x laemmli sample buffer at 100°C for 5 minutes and analyzed by immunoblotting for Ras.

### Mouse xenograft assay

This animal study was approved by the Institutional Review Board of Severance Hospital, Yonsei University College of Medicine. Approximately 4–6-week-old male *Balb C nu/nu*



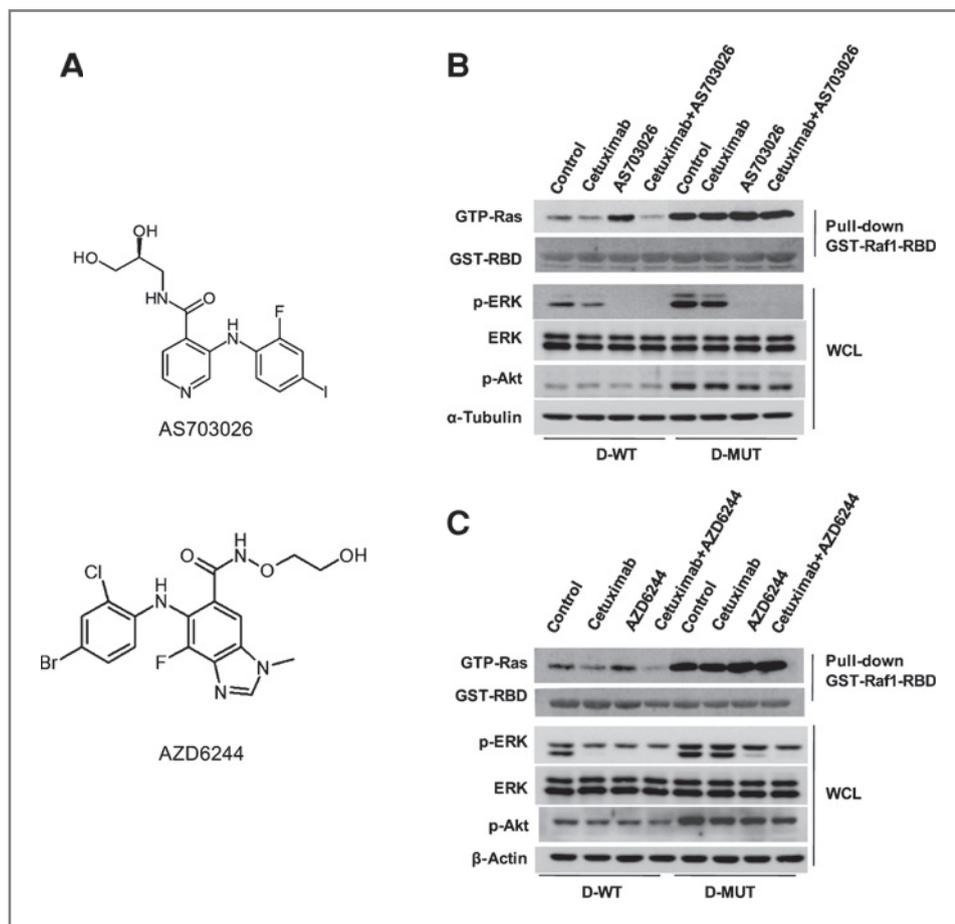
**Figure 1.** The *K-ras* mutation affects the responsiveness of D-WT and D-MUT cells to cetuximab. **A**, sensitivity of D-WT and D-MUT cells to cetuximab. D-WT and D-MUT cells were grown in RPMI, and treated with DMSO (control) or Cetuximab (5 $\mu$ g/mL) at every 24 hour for 72 hours. MTT assays were carried out at 24, 48, and 72 hours after treatment of drugs. **B** and **C**, *in vivo* effect of cetuximab on volume (**B**) and weight (**C**) of D-WT or D-MUT tumor in mouse xenograft model. Xenograft tumor model was established as described in Materials and Methods. Cetuximab were administrated to the nude mice bearing tumors intraperitoneally at dosage of 1 mg/mice, twice a week for 8 weeks (D-WT) or 4 weeks (D-MUT). Tumor volume was measured using callipers every week through experiment. **D**, paraformaldehyde fixed paraffin sections were incubated with anti-p-ERK, PCNA, or  $\beta$ -catenin antibody, followed by incubation with goat anti-mouse Alexa 555 secondary antibodies. Nuclei were counter stained by DAPI. Images were captured from nonhypoxic area and the tumor borders using laser scanning confocal microscopy (Carl Zeiss LSM510). Original magnification:  $\times 400$ .

mice were purchased from Slc Inc. Mice were housed in filter-topped shoebox cages with a MSRS environmental control system from Orient Biotech. Room temperature was maintained at 24°C with a relative humidity of approximately 40% to 70%. The mice were given a standard maintenance diet from Dae Han Bio Link. After acclimatization for 1 week,  $5 \times 10^6$  D-WT or MUT cells in 200  $\mu$ L of PBS: Matrigel (1:1) were subcutaneously injected to dorsal flank of athymic nude mice. When the mean values of tumor were between 100 and 200 mm<sup>3</sup>, mice were randomly divided into 4 groups (5 mice per group). Cetuximab was treated to mice intraperitoneally at dose of 1 mg/mice, twice a week. AS703026 and AZD6244, in a suspension of 0.5% methyl cellulose and 0.4% Tween 80, were injected by oral gavages once and twice daily at dosage of 10 mg/kg and 15 mg/kg, respectively. Tumor volume and body weight of mice were measured every 4 days. Tumor volumes were measured by Vernier calipers, following the formula of  $\pi/6 \times \text{length} \times \text{width} \times \text{height}$ . Animals were euthanized when tumor volume exceeded 1,500 mm<sup>3</sup>. For *in vivo* BrdU

labeling, mice were injected intraperitoneally with 100 mg/kg BrdU 4 hours before sacrifice. Twenty-eight days after treatment mice were sacrificed and tumors were excised and weighed and then fixed in paraformaldehyde or snap frozen in liquid nitrogen for further analysis.

#### Immunohistochemistry

For immunohistochemical analysis, 4  $\mu$ m paraffin sections were treated with 0.1% triton X-100 in PBS for 15 minutes and then block by 5% BSA and 1% NGS in PBS for 30 minutes. Primary and secondary antibodies were diluted with 1% BSA and 1% NGS in PBS. The primary antibody was omitted for negative control slides, which resulted in very low background labeling. Sections were incubated with primary antibodies, overnight at 4°C, followed by incubation with anti-mouse Alexa Flour 488 (1:500) and anti-rabbit Alex Flour 555 secondary antibodies (1:500) for 1 hour at room temperature, and counter stain by DAPI, and then mounted in Gel/Mount media (Biomedica Corporation). All incubations were carried out in



**Figure 2.** Effects of AS703026 and AZD6244 on Ras-ERK pathway in D-WT and D-MUT cells. **A**, chemical structures of AS703026 (top) and AZD6244 (bottom). **B** and **C**, effect of AS703026 (**B**) and AZD6244 (**C**) on Ras-ERK pathway in D-WT and D-MUT cells. D-WT and D-MUT cells were grown in RPMI, and treated for 24 hours with DMSO as a control, 5  $\mu\text{g/mL}$  cetuximab with/without 10  $\mu\text{mol/L}$  AS703026 or 50  $\mu\text{mol/L}$  AZD6244. The Effects of AS703026 or AZD6244 on Ras-ERK pathway in D-WT or D-MUT cells were measured by immunoblot analysis. GTP-loaded active Ras with a GST fusion-protein corresponding to the human Ras Binding Domain of Raf-1 (GST-Raf1-RBD) evaluated Ras activation. Immunoblot analyses were done using whole-cell lysates with anti-Pan-Ras, -p-ERK, -ERK, -p-Akt, or - $\alpha$ -tubulin antibody. The GTP-loaded Pan-Ras protein (RAS-GTP) was detected using anti-Pan-Ras antibody.

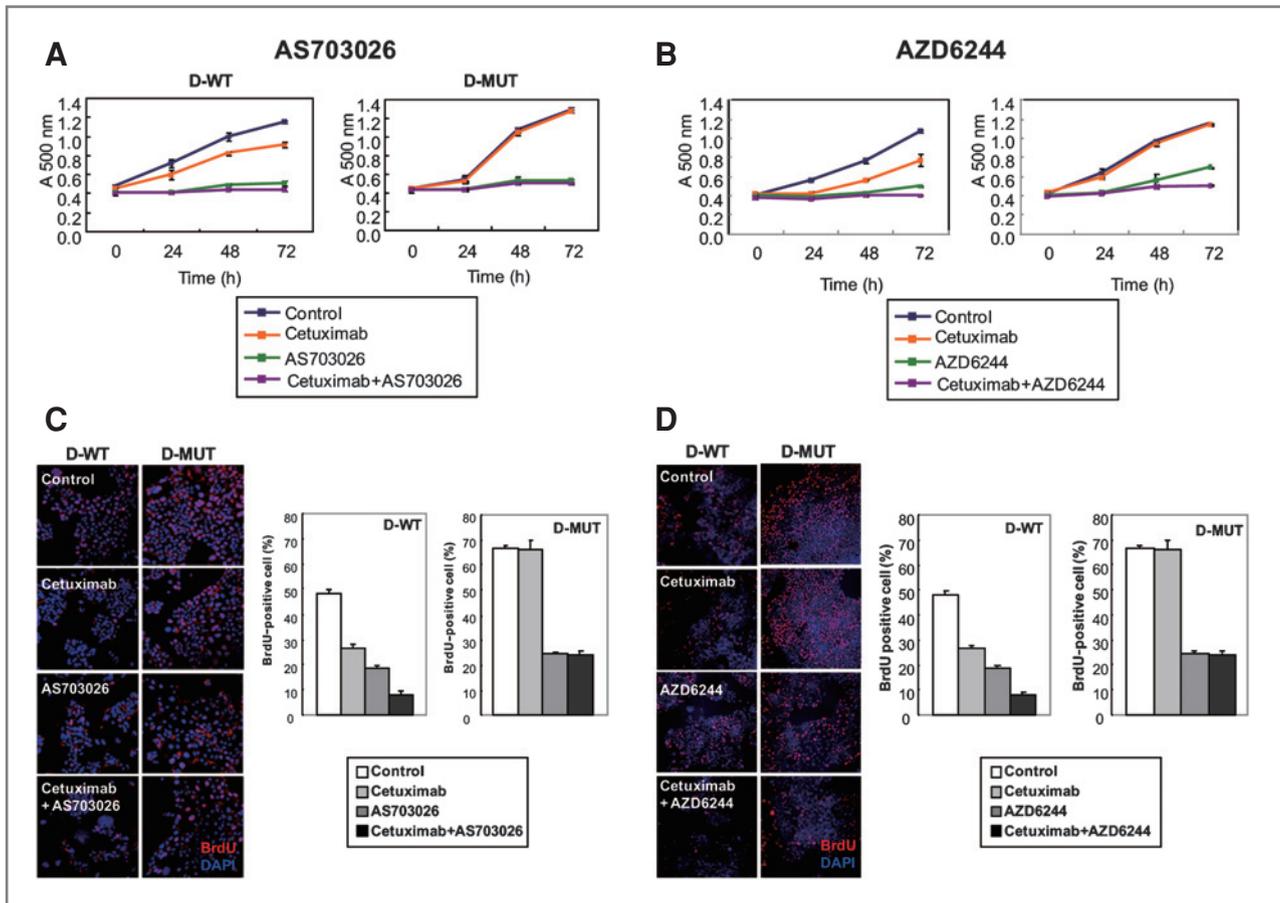
dark and humid chambers. The fluorescence signal was visualized using confocal microscopy (LSM510) at excitation wavelengths of 488 nm (Alexa Fluor 488), 543 nm (Alexa Fluor 555), and 405 nm (DAPI). At least 3 fields per section were analyzed to establish statistical significance.

## Results

### D-MUT colorectal cancer cells are resistant to cetuximab due to K-ras mutation

Cells retaining endogenous WT K-Ras (D-WT) and cells with a mutant allele of K-ras (D-MUT) in the genetic background of DLD-1 colorectal cancer cells (19) were adopted to study the sensitivity of anticancer drugs dependent on the mutational status of K-ras. DNA sequencing analysis confirmed the mutational status of K-ras in D-WT and D-MUT cells. (Supplementary Fig. S1). To determine responsiveness of EGFR mAb on K-ras mutation, D-WT and D-MUT cells expressing high level of EGFR were treated with cetuximab at every 24 hours for 72 hours. The proliferation of cells was measured by MTT analysis at 24, 48, and 72 hours after cetuximab treatment. As expected, D-MUT cells harboring mutated K-ras clearly showed resistance to cetuximab, whereas proliferation of the isogenic D-WT cells harboring WT K-Ras was suppressed by cetuximab (Fig. 1A). D-WT cell

growth was inhibited by 30% after cetuximab treatment as revealed by MTT analysis, whereas D-MUT cell growth was unchanged after 72 hours of treatment. To investigate the efficacy of cetuximab *in vivo*, mouse xenograft models were produced by injecting either D-WT or D-MUT cells subcutaneously into the dorsal flank of athymic nude mice. In the D-WT xenograft model, administration of cetuximab at dosage of 1 mg/mice twice a week for 8 weeks significantly reduced tumor size and tumor weight by 50% (Fig. 1B and 1C). In contrast, D-MUT tumors treated with cetuximab did not show a reduction in either volume (Fig. 1B) or weight (Fig. 1C) of tumors by the cetuximab therapy. Immunohistochemical analyses were done to confirm the effect of cetuximab on D-WT or D-MUT xenograft tumors (Fig. 1D). Positive staining for p-ERK was observed specifically around tumor borders, where a relatively nonhypoxic condition is maintained. Therefore, all images were obtained from these regions. The p-ERK staining was decreased in D-WT tumors treated with cetuximab, but was unaffected in D-MUT xenograft tumors with the same treatment (Fig. 1D). The staining patterns for PCNA, a proliferation marker, were similar to that of p-ERK, revealing that proliferation of both D-WT and D-MUT tumors correlate with activation status of the ERK pathway (Fig. 1D).  $\beta$ -catenin, as a negative control of staining, did not show any significant change by treatment of cetuximab (Fig. 1D).

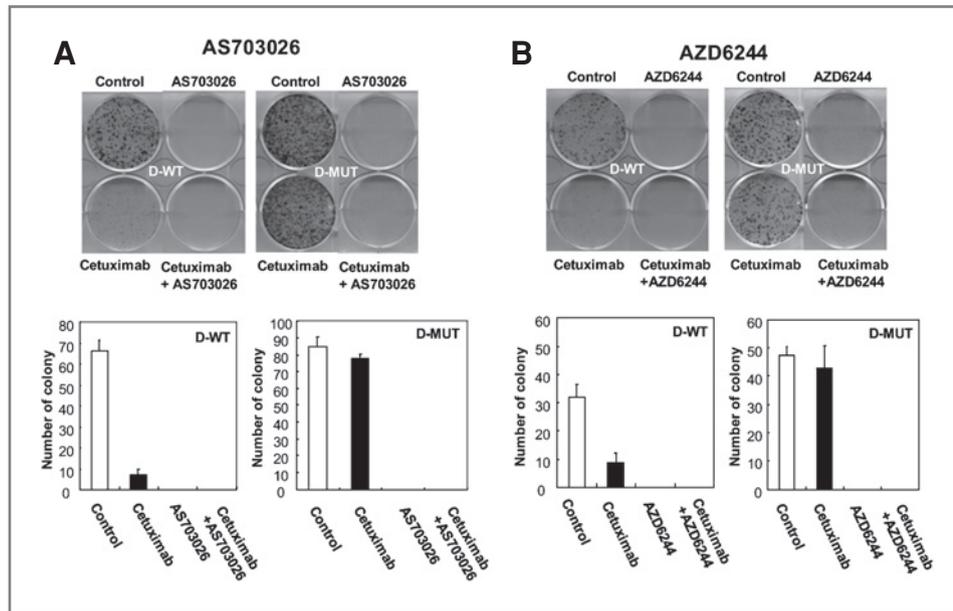


**Figure 3.** Effects of AS703026 and AZD6244 on cell proliferation of D-WT and D-MUT cells. A and B, cetuximab at 5  $\mu\text{g}/\text{mL}$  was applied to D-WT and D-MUT cells every 24 hour for 72 hours in combination with either 10  $\mu\text{mol}/\text{L}$  AS703026 (A) or 50  $\mu\text{mol}/\text{L}$  AZD6244 (B). MTT assays were done at 24, 48, and 72 hours after drug treatments. C and D, D-WT and D-MUT cells were treated for 24 hours with DMSO (control) or 5  $\mu\text{g}/\text{mL}$  cetuximab in combination with either 10  $\mu\text{mol}/\text{L}$  AS703026 (C) or and 50  $\mu\text{mol}/\text{L}$  AZD6244 (D). Then BrdU was added at a final concentration of 20  $\mu\text{mol}/\text{L}$  for 4 hours, and cells were fixed, permeabilized, incubated with anti-BrdU mAb, and finally incubated with goat anti-mouse Alexa 555 secondary antibodies. Cell nuclei were counterstained with DAPI. Cells were visualized by a laser scanning confocal microscopy (Carl Zeiss LSM510). The percentage of BrdU-positive cells was calculated from the total number of DAPI-stained cells (bottom), and error bars indicate the standard deviations of 3 independent analyses. Original magnification: C,  $\times 400$ ; D,  $\times 200$ .

### AS703026 and AZD6244 inhibit ERK pathway, proliferation, and transformation in cetuximab-resistant D-MUT cells

MEK inhibitors currently in clinical development, AS703026 and AZD6244 (Fig. 2A), which act downstream of K-Ras, were tested for their ability to overcome cetuximab resistance in D-MUT cells. In D-WT cells, cetuximab inhibited ERK activity by reducing GTP loading of Ras (Fig. 2B and C). In D-MUT cells, cetuximab did not reduce GTP loading of Ras or ERK activity attributed to the *K-ras* mutation (Fig. 2B and C). When D-MUT cells were also treated with AS703026 or AZD6244 (Fig. 2B and C), ERK activity was reduced, but no combination effect was observed. The inhibitory effect of 10  $\mu\text{mol}/\text{L}$  AS703026 on ERK activity was higher than that of 50  $\mu\text{mol}/\text{L}$  AZD6244 (Fig. 2B and C). The alternative MEK inhibitor U0126 showed identical effect on ERK activity (Supplementary Fig. S2). No significant change of Akt activity was observed when cetuximab, AS703026, or AZD6244 treated to both D-WT and D-MUT cells (Fig. 2B and C).

Effects of AS703026 and AZD6244 on cellular proliferation were measured using MTT and BrdU incorporation assays (Fig. 3). Treatment with cetuximab alone reduced proliferation of D-WT but not of D-MUT cells. Addition of AS703026 and AZD6244 reduced proliferation in both D-WT and D-MUT cells (Fig. 3A and B). When D-WT cells were treated with cetuximab, BrdU incorporation was decreased by 54%–65%, but was unaffected in D-MUT cells. BrdU incorporation in D-WT cells was reduced by 62.3% with the addition of AS703026 and by 67.2% with AZD6244, and in D-MUT cells by 63.2% with AS703026 and 61.3% with AZD6244 (Fig. 3C and D). The anchorage-independent growth of D-WT cells was inhibited by cetuximab, and that of D-MUT cells was not (Fig. 4A and B). Cellular transformation was reduced for both D-WT and D-MUT by treatment with AS703026 (Fig. 4A) or AZD6244 (Fig. 4B). However, no combination effects from treatment of cetuximab with either AS703026 or AZD6244 were observed in ERK activation, proliferation, or transformation of cells, although BrdU incorporation in D-WT cells did suggest combination effect (Fig. 3 and 4)



**Figure 4.** Effects of AS703026 and AZD6244 on cellular transformation of D-WT and D-MUT cells. A and B, D-WT and D-MUT cells were treated every 3 days for 7 days (D-MUT) or 14 days (D-WT) with DMSO (control) or 5  $\mu\text{g}/\text{mL}$  cetuximab combined with either 10  $\mu\text{mol}/\text{L}$  AS703026 (A) or 50  $\mu\text{mol}/\text{L}$  AZD6244 (B). Cells were stained with 0.5% crystal violet in 20% ethanol, and then foci were photographed. Quantitative data for the relative percentages of foci numbers are represented at the bottom, with error bars indicating the standard deviation of 3 independent analyses.

### AS703026 and AZD6244 inhibit tumor growth of cetuximab-resistant tumor attributed by *K-ras* mutation

Antitumor effects of AS703026, AZD6244, and cetuximab were measured using mouse tumor xenograft models. The representative gross images for tumor on athymic mice bearing tumor are shown in Fig. 5A and B. Cetuximab treatment did not reduce the size of D-MUT xenograft tumors (Fig. 5C and D). However, both volume (Fig. 5C) and weight (Fig. 5E) of tumors caused by D-MUT cells were reduced by 60% by AS703026, and this correlates with the cell-based *in vitro* studies. Treatment with AZD6244 showed a similar growth inhibitory effect on tumor volume decreased by 71% (Fig. 5D) and weight by 68% (Fig. 5F). In agreement with the cell studies, no combination effect was observed when AS703026 or AZD6244 (Fig. 5). We did not observe any statistically significant changes in body weight of mice used through the both experiments (Supplementary Fig. S3).

Immunohistochemical analyses were done to confirm the mechanisms of action of AS703026, AZD6244, and cetuximab on D-MUT xenograft tumors (Fig. 6). In AS703026 and AZD6244 administered D-MUT tumors, however, p-ERK staining decreased markedly (Fig. 6). The ATF2 activity monitored by anti-p-ATF2 (T71) antibody was reduced by treatment of AS703026 or AZD6244 in D-MUT tumors, indicating that ERK activity inhibits the regulation of target genes (Fig. 6). The Akt activity was not significantly reduced by cetuximab or MEK inhibitor treatment in D-MUT tumors (Fig. 6).  $\beta$ -catenin did not show any significant change by cetuximab therapy (Fig. 6).

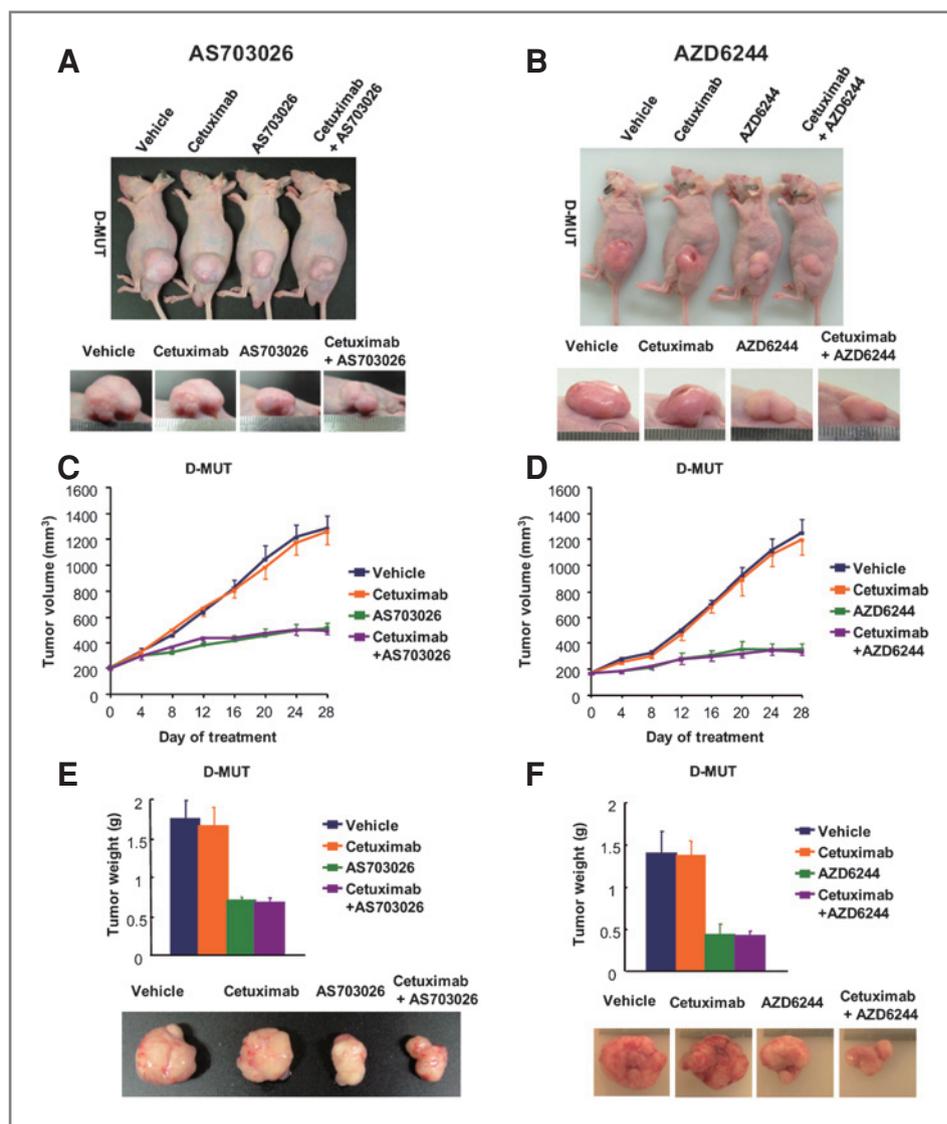
### Discussion

Since the first MEK inhibitor, PD98059 have been developed, other numerous MEK inhibitors have also been developed. Undesirable pharmaceutical properties or side effects

resulted in none of the early MEK inhibitors, including U0126 and RO 09-2210, progressing to clinical trials (23). By cell-based screening or modification from the original MEK inhibitor, 11 MEK inhibitors have entered clinical trials. CI-1040 (Pfizer) was the first MEK1/2 inhibitor to enter clinical trials (21). Despite higher selectivity of CI-1040 to MEK1/2 inhibition, this drug has been disclosed after Phase II because of insufficient antitumor activity, poor solubility, and low efficacy (21). A following clinical trial of a second generation MEK1/2 inhibitor PD0325901 (Pfizer), an analogue of CI-1040, was also stopped in phase II by severe toxicity including blurred vision as well as neurotoxicity. Here, we investigated the use of AS703026 (Merck Serono) and AZD6244 (AstraZeneca), which are in clinical trials, to check the effects of MEK1/2 inhibition on *K-ras* mutated colorectal cancer (20, 21). The results of the phase I and II studies of AZD6244 were reported with evidence of only a single-agent antitumor activity in patients with non-small cell lung cancer, advanced melanoma, or mCRC as well as lack of radiographic response in patients with advanced or metastatic hepatocellular carcinoma (24–28). However, other phase II trials in a variety of tumor types are currently in process (21).

AS703026 was most recently developed as a highly selective, ATP noncompetitive allosteric MEK1/2 inhibitor. Phase I clinical trials of AS703026 are underway to test its inhibitory effects on multiple solid tumors (29). Multiple myeloma (MM) cells are inhibited by AS703026 regardless of *Ras* and *BRAF* mutation when it is administered in combination with multiple conventional, novel, and emerging anti-MM therapies (30). This study shows efficacy of both AZD6244 and AS703026 on colorectal cancer with *K-ras* mutation. When ligands bind to activate EGFR, both the ERK and PI3K-Akt pathways are activated (18). Ras protein directly interacts with the p110 subunit of PI3K to activate Akt (31). Both ERK and PI3K-Akt pathways are strongly implicated in cell proliferation and

**Figure 5.** Effects of AS703026 and AZD6244 on the tumor size of cetuximab-resistant tumor caused by *K-ras* mutation. A and B, 5 athymic nude mice were treated for 28 days by oral gavage with vehicle or with cetuximab combined with either 10 mg/kg AS703026 (left) once daily or 15 mg/kg AZD6244 (right) twice daily. Gross images showing representative cases treated with AS703026 (A) and AZD6244 (B), with enlarged tumor images for each case presented at the bottom. C and D, the tumors volume of mice treated with vehicle or cetuximab with/without either AS703026 (C) or AZD6244 (D) were measured with Vernier callipers every 4 days. E and F, after sacrifice, tumor weights were measured by an electronic balance from the tumors of mice treated with vehicle or cetuximab with/without either AS703026 (E) or AZD6244 (F). Gross images from representative excised tumors are shown at the bottom.

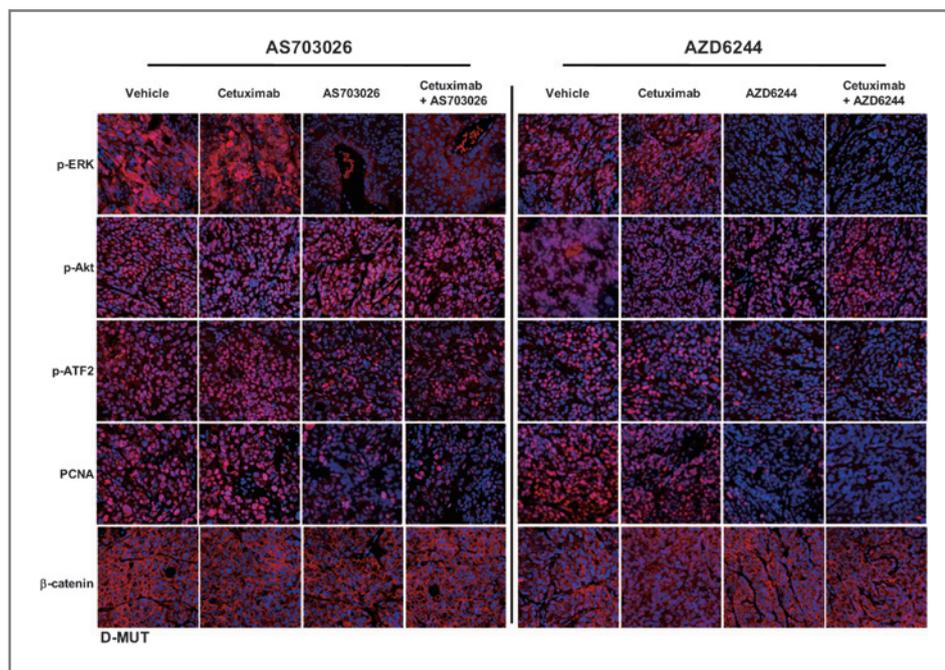


survival (32). Combined therapy with MEK and PI3K inhibitors had a synergistic inhibitory effect on non-small cell lung cancer cells affected by the *K-ras* mutation (33). Our study indicates that inhibitory effects of AS703026 and AZD6244 on tumor volume in the xenograft assay did not abolish tumor growth. We observed no inhibition of Akt activity by either cetuximab or MEK inhibitor in D-MUT tumors due to oncogenic mutation of *K-ras*. Our results indicate the simultaneous blockade of Ras-ERK and PI3K-Akt pathways may be more efficacious in the treatment of cancers attributed by *K-ras* mutation. The recent announcement of a collaboration between Merck and AstraZeneca to test combination cancer therapy using MEK inhibitor AZD6244 (AstraZeneca) and Akt inhibitor MK-2206 (Merck) further support importance of the combinatory therapy related with *ras* mutation (21).

We observed that both AS703026 and AZD6244 increased GTP-loading of Ras. This increment of GTP-loading of Ras may be caused by desensitization of Ras activation through

the disassociation of the Grb2-Sos complex by phosphorylating Sos (34). Our observation also correlates with the previous report that MEK inhibition blocked phosphorylation and dissociation of Sos from Grb2, resulting in prolonged Ras activation (35). When AS703026 or AZD6244 were treated with a combination of cetuximab, this negative feedback regulation was thoroughly diminished by targeting EGFR, the upstream signaling regulator.

Interestingly, new DNA synthesis of D-WT cells, monitored by BrdU incorporation, was synergistically reduced by MEK inhibitor and cetuximab although we did not observe the synergy effects in the measurement of cellular transformation by foci formation assay. The synergy effect observed in these studies indicates that an alternative route for transmission of proliferation signal is present only in the wild-type DLD-1 cells. Somatic mutation of *PI3K* in the parent DLD-1 cells may not allow transferring downstream signaling to Akt (36). Therefore, PI3K-Akt pathway may not be involved in this synergistic effect.



**Figure 6.** Effect of AS703026 or AZD6244 on the activations of downstream pathways of Ras in D-MUT xenograft tumors. Immunohistochemical analyses of activation of the Ras downstream components in the Ras-ERK and PI3K-Akt pathways. Paraformaldehyde fixed paraffin sections were incubated with anti-p-ERK, p-Akt, p-ATF2, PCNA, or  $\beta$ -catenin antibody, followed by incubation with goat anti-mouse Alexa 555 secondary antibodies. Nuclei were counter stained by DAPI. Images were captured from nonhypoxic area and the tumor borders using laser scanning confocal microscopy (Carl Zeiss LSM510). Original magnification:  $\times 400$ .

One potential route attributing the synergy effect may be the pathway involving RalGDS. The RalGDS can directly interact with GTP-bound active form of Ras protein through their Ras binding domain (RBD) (37), and interaction between GTP-Ras and RalGDS promote the translocation of RalGDS to the plasma membrane where it activates Ral (38). The RalGDS-Ral pathway has been shown to be involved in regulation of various transcription factors, such as Rlf, c-Jun, and ATF2, to promote cell proliferation (39–41). In addition, RalGDS promote Akt activation by PDK1 as a scaffold protein (42).

Here, we used D-WT and D-MUT cell, the isogenic colorectal cancer cell lines, as pair. The usage of these cell lines eliminates the possibility of partial effect by wild-type *K-Ras* in *K-ras* mutated cancer cells, when compared with the several previous trials related with therapeutic potential of MEK inhibitors on various cancer cells (43–46). The data indicate clear resistance to EGFR mAb in the *K-ras* mutated cell line D-MUT, an advantage over most colorectal cancer cells that have heterozygous *K-ras* mutations. The BRAF inhibitor Sorafenib was previously suggested to overcome the cetuximab resistance of *K-ras* mutated colorectal cancer, although the study involved only an *in vitro* system (47). This study provides *in vivo* evidence for the cetuximab resistance of *K-ras* mutations and therapeutic strategy to overcome it using xenograft tumor model of CRC harboring an isogenic *K-ras* mutation. In the era of personalized medicine, our results suggest that the paired isogenic colorectal cancer cell

can be used as a drug screening system to identify the overcoming effect related with cetuximab resistance in *K-ras* mutated colorectal cancer.

### Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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## MEK1/2 Inhibitors AS703026 and AZD6244 May Be Potential Therapies for *KRAS* Mutated Colorectal Cancer That Is Resistant to EGFR Monoclonal Antibody Therapy

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