Wild-Type BRAF Is Required for Response to Panitumumab or Cetuximab in Metastatic Colorectal Cancer

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Terms in blue are defined in the glossary, found at the end of this article and online at www.jco.org.

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ABSTRACT

Purpose

Cetuximab or panitumumab are effective in 10% to 20% unselected metastatic colorectal cancer (CRC) patients. KRAS mutations account for approximately 30% to 40% patients who are not responsive. The serine-threonine kinase BRAF is the principal effector of KRAS. We hypothesized that, in KRAS wild-type patients, BRAF mutations could have a predictive/prognostic value.

Patients and Methods

We retrospectively analyzed objective tumor responses, time to progression, overall survival (OS), and the mutational status of KRAS and BRAF in 113 tumors from cetuximab- or panitumumab-treated metastatic CRC patients. The effect of the BRAF V600E mutation on cetuximab or panitumumab response was also assessed using cellular models of CRC.

Results

KRAS mutations were present in 30% of the patients and were associated with resistance to cetuximab or panitumumab (P = .011). The BRAF V600E mutation was detected in 11 of 79 patients who had wild-type KRAS. None of the BRAF-mutated patients responded to treatment, whereas none of the responders carried BRAF mutations (P = .029). BRAF-mutated patients had significantly shorter progression-free survival (P = .011) and OS (P < .0001) than wild-type patients. In CRC cells, the introduction of BRAF V600E allele impaired the therapeutic effect of cetuximab or panitumumab. Treatment with the BRAF inhibitor sorafenib restored sensitivity to panitumumab or cetuximab of CRC cells carrying the V600E allele.

Conclusion

BRAF wild-type is required for response to panitumumab or cetuximab and could be used to select patients who are eligible for the treatment. Double-hit therapies aimed at simultaneous inhibition of epidermal growth factor receptor and BRAF warrant exploration in CRC patients carrying the V600E oncogenic mutation.

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INTRODUCTION

Patients with metastatic colorectal cancer (mCRC) have a 5-year survival rate of less than 10%. Cetuximab and panitumumab, two monoclonal antibodies (MoAb) targeting epidermal growth factor receptor (EGFR), have recently entered clinical practice and have proven to be effective in providing clinical benefit in approximately 10% to 20% of patients. Both molecules bind to the extracellular domain of EGFR, thus leading to inhibition of its downstream signaling. EGFR is a transmembrane tyrosine kinase receptor that, on ligand binding, triggers two main signaling pathways. These include the RAS-RAF-MAPK axis, which is mainly involved in cell proliferation, and the PI3K-PTEN-AKT pathway, which is mainly involved in cell survival and motility. Cetuximab and panitumumab are registered for mCRC patients whose tumors express EGFR protein as determined by immunohistochemistry. However, it has been clearly demonstrated that this method is not predictive of treatment efficacy. On the contrary, recent data indicate that EGFR gene status evaluated by fluorescent in situ hybridization or chromogenic in situ hybridization may predict response to these MoAbs. We and others have previously shown, at the preclinical and clinical level, that the presence of mutated KRAS alleles is an independent predictive marker of anti-EGFR MoAb resistance. On the basis of these results, the European Union drug regulatory body, the European Medicines Agency, has approved the use of panitumumab only for mCRC patients whose tumors display wild-type KRAS. However, the occurrence of KRAS mutations only accounts for approximately 30% to 40% of...
nonresponsive patients. Therefore, the identification of additional genetic determinants of primary resistance to EGFR-targeted therapies in colorectal cancers (CRCs) is important at least for two reasons. The first is to prospectively identify patients who should not receive either cetuximab or panitumumab, thus avoiding their exposure to ineffective and expensive therapy. Second, understanding the molecular basis of primary resistance to EGFR-targeted MoAb therapies could allow the rationale design of alternative treatment strategies. We hypothesized that, in the absence of KRAS mutations, resistance to anti-EGFR treatments could be caused by alterations of other members of the RAS-RAF-MAPK pathway. Using genetic analysis of mCRCs from cetuximab- or panitumumab-treated patients and cellular models of CRC, we assessed whether BRAF mutations affect the response to therapies based on EGFR-targeted MoAbs. Because BRAF mutations are linked to microsatellite instability (MSI), a condition generally associated with better prognosis and resistance to standard chemotherapy, we also investigated MSI in our cohort of treated patients.

PATIENTS AND METHODS

Patient Population and Treatment Regimens

We retrospectively analyzed 113 patients with histologically confirmed mCRC either at Ospedale Niguarda Ca’ Granda (Milan, Italy) or at the Institute of Pathology (Locarno, Switzerland). Patients evaluated in this study were selected based on evidence that treatment outcome could be attributable only to administration of either panitumumab or cetuximab. Patients were enrolled onto clinical trials (64 of 113 patients; see Appendix, online only) or received panitumumab or cetuximab as per label indication. For patients who experienced progression on irinotecan-based chemotherapy, cetuximab was administered in combination with irinotecan at the same dose and schedule previously used. In all patients, refractoriness to irinotecan was defined as documented disease progression by comparison of computed tomography or magnetic resonance imaging scans during or within 3 months of receiving an irinotecan regimen (administered for at least 6 weeks). Besides the earlier mentioned inclusion criteria, the availability of a tumor sample qualitatively and quantitatively suitable for molecular analyses was also a requirement for being considered in the present study. All patients had EGFR expression in their tumor specimens in ≥ 1% of malignant cells assessed by immunohistochemistry with the Dako EGFR PharmDx kit (DakoCytomation, Glostrup, Denmark). Patients’ baseline characteristics, disease stage, and number of previous lines of therapy are listed in Table 1. Treatment was continued until progressive disease (PD) or toxicity occurred, according to the standard criteria.

Clinical Evaluation and Tumor Response Criteria

Clinical response was assessed every 6 to 8 weeks with radiologic examination (computed tomography or magnetic resonance imaging). The Response Evaluation Criteria in Solid Tumors were adopted for evaluation, and objective tumor response was classified as partial response (PR), stable disease (SD), or PD. Patients with SD or PD were defined as nonresponders. Two independent oncologists and radiologists verified, in a blinded manner, the clinical response for all patients.

Molecular Analyses

Formalin-fixed, paraffin-embedded tumor blocks were reviewed for quality and tumor content, and a single representative tumor block from each patient, containing at least 70% of neoplastic cells, was selected. Genomic DNA was extracted as previously described. The status of MSI was assessed by the analysis of the microsatellite loci included in the panel of Bethesda (BAT25, BAT26, D2S123, D5S346, and D17S250), as previously reported. MSI was confirmed by the presence of an additional peak in tumor sample compared with normal paired tissue. MSI was defined as being present when more than 30% of loci showed instability.

Table 1. Baseline Patient Characteristics by KRAS and BRAF Status

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mutant KRAS</th>
<th>Mutant BRAF</th>
<th>Wild-Type KRAS and BRAF</th>
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<td>12313</td>
<td>151513</td>
<td>123</td>
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<td>43-68</td>
<td>26-85</td>
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<td>Site of primary disease</td>
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<td>63</td>
<td>63</td>
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<td>Rectum</td>
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<td>Cetuximab plus chemotherapy</td>
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<td>No. of prior lines of chemotherapy</td>
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<td>1 2 2 1</td>
<td>1 2 2 1</td>
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</tr>
</tbody>
</table>

Abbreviations: EGFR, epidermal growth factor receptor; MoAb, monoclonal antibody.

aThirteen patients received cetuximab as front-line therapy.
The level of significance was set at \( p < 0.05 \) (two-tailed Fisher’s exact test) to check possible significance. The objective tumor response was the end point of our exploratory study. Qualitative comparisons of objective response to therapy (responders [PR] vs nonresponders [PD + SD]) and gene mutations as predictors were assessed in a cohort of 113 patients (41 females and 72 males, with a mean age 63 years) who had received either panitumumab- or cetuximab-based chemotherapy. Twenty-four patients (21%) achieved PR, and the median duration of response was 25 weeks (range, 10 to 128 weeks). Patient characteristics by KRAS mutational status are listed in Table 1. KRAS exon 2 mutations were found in 34 (30%) of 113 analyzed patients. KRAS mutations were detected in two (8%) of 24 responsive patients but in 32 (35%) of 89 nonresponders (Fig 1). The data confirm that the presence of KRAS mutations correlates with lack of response to anti-EGFR MoAb therapy (two-tailed Fisher’s exact test, \( p = 0.011 \)).

The follow-up analyses indicated that patients carrying a KRAS-mutated tumor displayed a shorter PFS (log-rank test, \( p = 0.0275 \); Fig 2A). No statistically significant differences were observed by OS analysis (\( p = 0.0869 \); Fig 2B).

Data were analyzed using the Stata 9.1 package (Stata Corp, College Station, TX).

**RESULTS**

**Mutational Profiling of KRAS and Response of Patients Treated With Cetuximab or Panitumumab**

The mutational status of KRAS was assessed in a cohort of 113 patients (41 females and 72 males, with a mean age 63 years) who had received either panitumumab- or cetuximab-based chemotherapy. Twenty-four patients (21%) achieved PR, and the median duration of response was 25 weeks (range, 10 to 128 weeks). Patient characteristics by KRAS mutational status are listed in Table 1. KRAS exon 2 mutations were found in 34 (30%) of 113 analyzed patients. KRAS mutations were detected in two (8%) of 24 responsive patients but in 32 (35%) of 89 nonresponders (Fig 1). The data confirm that the presence of KRAS mutations correlates with lack of response to anti-EGFR MoAb therapy (two-tailed Fisher’s exact test, \( p = 0.011 \)). The follow-up analyses indicated that patients carrying a KRAS-mutated tumor displayed a shorter PFS (log-rank test, \( p = 0.0275 \); Fig 2A). No statistically significant differences were observed by OS analysis (\( p = 0.0869 \); Fig 2B).

![Fig 1. KRAS and BRAF mutations correlate with lack of response to treatment with monoclonal antibodies targeting epidermal growth factor receptor. The number of responders and nonresponders (stable disease [SD] + progressive disease [PD]) is indicated according to KRAS or BRAF mutational status. The percentage of patients displaying partial response (PR), SD, or PD is shown in the pie charts. mCRC, metastatic colorectal cancer.](https://www.jco.org/)

![Fig 2. KRAS mutations are associated with shorter progression-free survival (PFS). (A) Patients with wild-type KRAS tumors displayed a better PFS than patients with KRAS-mutated tumors (log-rank test, \( P = 0.0275 \)). (B) Patients carrying KRAS-mutated tumors tended to have shorter overall survival. However, this difference did not reach statistical significance (log-rank test, \( P = 0.0869 \); ns, not significant.)](https://www.jco.org/)
Mutational Profiling of BRAF in Wild-Type KRAS Patients Treated With Cetuximab or Panitumumab

We and others have previously reported that KRAS and BRAF mutations are mutually exclusive in CRC.26,27 This relationship was experimentally verified in our sample set, and we found that none of the KRAS-mutated samples carried concomitant BRAF mutations, or vice versa. The only type of BRAF mutation found in our cohort was the previously described V600E substitution, which was detected in 11 patients (13%). In all patients, the amino acid change was a result of the classic GTG→GAG mutation at position 1799 of the BRAF nucleotide sequence. Patient characteristics by BRAF mutational status are listed in Table 1.

BRAF V600E Allele Impairs the Response to Cetuximab or Panitumumab

The presence of BRAF mutations was inversely associated with response to therapy (Fig 1). Significantly, none of 22 KRAS wild-type patients who experienced PR displayed BRAF mutations, whereas 11 (14.0%) of 79 nonresponder patients carried the BRAF V600E mutation (two-tailed Fisher’s exact test, P = .029). These data indicate that occurrence of oncogenic BRAF alleles negatively interferes with the clinical response to MoAbs targeting EGFR.

BRAF Mutations Are Associated With Shorter PFS and OS

We assessed how the occurrence of BRAF mutations affected clinical parameters such as PFS and OS. The follow-up analyses indicated that within the subgroup of KRAS wild-type patients, those carrying a BRAF-mutated tumor had a shorter PFS and OS than BRAF wild-type patients (log-rank test, P = .0010 and P < .0001, respectively; Figs 3A and 3B). In the entire cohort of patients, independently from KRAS mutational status, individuals with BRAF-mutated tumors still displayed shorter PFS and OS than patients with BRAF wild-type tumors (log-rank test, P = .0107 and P < .0001, respectively). This significant association indicates that the presence of BRAF V600E mutation correlates with a worse prognosis. MSI has been linked both to the occurrence of BRAF mutation and to improved prognosis in sporadic CRC patients treated with fluorouracil-based regimens.19,28-30 MSI was assessed in a subset of patients, including 10 with BRAF-mutated samples, 24 with KRAS-mutated samples, and 41 with samples that were wild type for both genes. We identified MSI in one (1.3%) of these 75 patients, and this patient had a sample that was wild type for both KRAS and BRAF. Importantly, none of the tested BRAF-mutated tumors displayed MSI, indicating that this factor is unlikely to affect the OS results and the effect on the efficacy of EGFR-targeted therapies presented earlier.

BRAF V600E Allele Impairs the Response of CRC Cells to Cetuximab or Panitumumab

The genetic profiling of CRCs showed that the presence of mutated BRAF negatively interferes with clinical response to EGFR-targeted MoAbs. We hypothesized that oncogenic activation of BRAF by the V600E mutation could bypass (short circuit) the EGFR-initiated signaling cascade. To assess the effect of the BRAF V600E mutation on response to cetuximab or panitumumab, we used cellular models of CRC. Specifically, we used a CRC line, DiFi, carrying a KRAS wild-type mutation on response to cetuximab or panitumumab, we used cellu-

![Fig 3.](image-url)
impairs the therapeutic potential of cetuximab and panitumumab in CRC cells. To assess whether this finding could be replicated in cancer cells in which the BRAF V600E was naturally present, we used HT-29 and COLO-205, which are two cell lines derived from colorectal tumors in which the mutation had been previously detected. After independently verifying that both lines carried the BRAF V600E allele (and were wild type for KRAS), we found that HT-29 and COLO-205 are highly refractory to cetuximab and panitumumab treatment (Figs 4A and 4B).

Combinatorial Targeting of EGFR and BRAF in CRC Cells Carrying the BRAF V600E Allele

The mutational profiling of CRCs showed that the presence of BRAF mutations renders cancer cells unresponsive to EGFR-targeted MoAb therapies. We hypothesized that the pharmacologic inhibition of BRAF might restore the sensitivity to cetuximab or panitumumab in CRC cells carrying the V600E mutation. Sorafenib, a clinically approved small-molecule kinase inhibitor, was used to pharmacologically target BRAF.32

When DiFi-BRAF, COLO-205, and HT-29 cells were treated with a combination of cetuximab and sorafenib, we found a dramatically reduced viability in all three cellular models (Figs 4C, 4D, and 4E), whereas single agents, alone, had limited effects. To dissect the mechanism through which the combinatorial treatment synergistically affected cancer cells carrying the BRAF V600E mutation, we measured its effects both on cell cycle and on apoptosis. The combination of cetuximab and sorafenib limitedly affected proliferation compared with sorafenib alone (Fig 5A), whereas it showed a prominent proapoptotic effect, as demonstrated by the massive increase of caspase 3/7 activation observed in HT-29 and COLO-205 cells (Fig 5B).

DISCUSSION

Cetuximab and panitumumab have shown efficacy in approximately 10% to 20% of mCRC patients. It is now emerging that genetic alterations of EGFR and its downstream signaling effectors may predict the efficacy of EGFR-targeted MoAbs.8-15 In particular, the role of oncogenic KRAS has been extensively analyzed, leading to the conclusion that the occurrence of KRAS mutations represents a predictive marker of anti-EGFR MoAb resistance.8-10,13-17 However, KRAS mutations only account for 30% to 40% of nonresponsive patients. Therefore, the identification of additional genetic determinants of primary resistance to EGFR-targeted therapies in CRC is clearly a priority. Genetic and biochemical evidence indicates that BRAF is the principal downstream effector of KRAS.33,34 Whether and to what extent the oncogenic activation of BRAF (a serine-threonine kinase mutated in approximately 10% of CRCs) affects the response to anti-EGFR MoAbs has been only marginally investigated.13 By analyzing a larger cohort of mCRCs patients, we found that BRAF mutations are associated with resistance to EGFR-targeted MoAb therapies. Our data indicate that the role of BRAF mutations in patients treated with EGFR-targeted drugs is similar to that played by mutated KRAS. We propose that the combined mutational analysis of both KRAS and
BRAF could be used to prospectively select mCRC patients eligible for EGFR-targeted MoAb treatment, with evident medical and economic implications. However, our findings need to be formally confirmed in a randomized clinical trial comparing an experimental arm containing cetuximab or panitumumab with a control arm without this targeted therapy.

Despite the predictive value of both KRAS and BRAF mutations, in our cohort, there was still a significant percentage of nonresponsive patients (41%) who did not have mutations in either gene. Therefore, further molecular markers are needed to better define patients who are unlikely to benefit from EGFR-targeted MoAb treatment.

The present study also shows that patients carrying a BRAF point mutation have a shorter PFS and OS. This is in accordance with previous data indicating that CRCs with BRAF mutations have a more aggressive phenotype.28 It has been previously reported that BRAF mutations are more frequently detected in MSI-sporadic CRC compared with microsatellite-stable CRC (up to 50% v up to 12%, respectively).28-30 Considering that MSI is a condition generally associated with better prognosis and with resistance to standard chemotherapies,19 we investigated this marker in our series. The tumors in which we detected BRAF mutations did not show MSI, thus excluding that the results could be a result of a general mechanism of MSI-dependent drug resistance. Therefore, the prognostic and predictive value of BRAF mutations in anti-EGFR–treated mCRC patients does not depend on the MSI status. The frequency of MSI in our cohort of advanced CRC patients is significantly lower (1.3%) with respect to the expected rate (at least 15%) when all stages of sporadic CRC are analyzed. We analyzed 30 additional mCRC patients (not treated with EGFR-targeted therapies), none of whom showed MSI. Therefore, our cumulative results indicate that only one of 105 advanced CRC patients showed MSI. A stage selection may account for these results because our cohort included only metastatic patients. In fact, our frequency is similar to that reported in a previous study that found only five patients (2.7%) with MSI in 190 mCRC patients.35 Thus, our results are well in accordance with the notion that the MSI phenotype
is associated with better prognosis\textsuperscript{19} and with a reduced likelihood of metastasis in patients with CRC.\textsuperscript{36}

Although our study suggests a strong correlation of BRAF mutations in mCRC with a worse prognosis, further studies are needed to fully evaluate this marker with and without EGFR-targeted therapies, similar to what has been done for KRAS.\textsuperscript{18}

To assess, at the molecular level, how the BRAF mutation could influence the response to anti-EGFR MoAbs, we exploited cellular models of CRC. We found that the occurrence or the exogenous introduction of the BRAF V600E allele in CRC cells dramatically impairs their response to cetuximab or panitumumab. These results have two relevant implications. First, they show that the presence of the V600E allele directly affects the response to EGFR-targeted MoAbs at the cellular level. Second, they suggest that the correlation between the occurrence of BRAF mutation and the ineffective clinical response to cetuximab or panitumumab is not generically a result of the poorer prognosis of BRAF-mutated tumors. Our cell-based analysis also shows that even BRAF-mutated CRC cells can potentially respond to EGFR-targeted MoAbs if the BRAF inhibitor sorafenib is administered concomitantly with cetuximab or panitumumab. Of note, either drug alone had limited activity, indicating that they act synergistically. These data indicate that in BRAF-mutated tumors, the therapeutic effect of cetuximab or panitumumab could be restored by two-hit approaches aimed at blocking the EGFR pathway at multiple locations. In addition to sorafenib, other compounds targeting either BRAF (PLX4032) or its downstream effectors (ARRY-162, AZD6244, and PD0325901) are in clinical development\textsuperscript{37} and could be exploited in combination with EGFR-targeted MoAb therapy.

Overall, the present study has at least two implications that could be relevant for the therapy of mCRC. The first is that patients whose tumors bear the BRAF V600E allele are not likely to experience significant clinical benefit on either cetuximab or panitumumab treatment. Therefore, BRAF mutation analysis could be used as an additional tool for the selection of mCRC patients who might benefit from EGFR-targeted MoAb therapies. The second is that clinical trials designed to test multiple therapies with EGFR and BRAF/\textit{MAPK} inhibitors should be conceived for mCRC patients in whom the KRAS/BRAF pathway is oncogenically activated. Because cetuximab, panitumumab, and sorafenib are already approved for clinical use, the data presented here could find immediate clinical evaluation in phase II trials in patients who have BRAF-mutated tumors.

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Appendix

Patient Population and Treatment Regimens

Patients gave informed consent and were treated with panitumumab- or cetuximab-based regimens at Ospedale Niguarda Ca’ Granda (Milan, Italy) or at the Oncology Institute of Southern Switzerland (Bellinzona, Switzerland). Patients evaluated in this study were selected based primarily on evidence that treatment outcome could be attributable only to administration of either panitumumab or cetuximab. Most patients were enrolled on clinical trials (64 of 113 patients) or received panitumumab or cetuximab as per label indication.

Cetuximab monotherapy was administered as first-line treatment in the EMR 202-600 (Pessino A, Artale S, Sciallero S, et al. Ann Oncol 19:711-716, 2008) phase II trial (12 patients) and as third-line treatment in the monotherapy group of the Bowel Oncology with Cetuximab Antibody trial (Cunningham D, Humblet Y, Siena S, et al. N Engl J Med 351:337-345, 2004) for patients refractory to irinotecan (four patients). Cetuximab as monotherapy was administered at a loading dose of 400 mg/m² intravenously, followed by 250 mg/m² once a week until progression.

Cetuximab plus irinotecan was assigned as third-line treatment in the combination group of the Bowel Oncology with Cetuximab Antibody (Cunningham D, Humblet Y, Siena S, et al. N Engl J Med 351:337-345, 2004) phase II trial (six patients), in the MABEL trial (Wilke H, Glynne-Jones R, Thaler J, et al. J Clin Oncol [in press]) for patients refractory to irinotecan (11 patients), as second-line treatment in the EMR 62 202-025 trial (five patients, all of whom showed progressive disease as best response), or as per label in patients refractory to irinotecan (24 patients). Cetuximab was administered in the same dose and schedule as for the monotherapy group, and irinotecan was administered in the same dose and schedule to which every patient had previously become resistant; both were administered until disease progression. In all patients, refractoriness to irinotecan was defined as documented disease progression during or within 3 months of receiving an irinotecan regimen (administered for at least 6 weeks). Cetuximab plus capicitabine and oxaliplatin were administered as first-line treatment in the SWS-SAKK-41/04 trial (Borner M, Koeberle D, Von Moos R, et al. Ann Oncol 19:1288-1292, 2008) (three patients), all of whom showed progressive disease as best response.

Panitumumab 6 mg/kg administered intravenously every 2 weeks until progression was allocated as third-line or fourth-line treatment for patients resistant to regimens consisting of oxaliplatin and irinotecan in the phase III ABX-EGF 20020408 trial (Van Cutsem E, Peeters M, Siena S, et al. J Clin Oncol 25:1658-1664, 2007) (13 patients) and cross-over ABX-EGF 20020194 trial (Van Cutsem E, Siena S, Humblet Y, et al. Ann Oncol 19:92-98, 2008) (11 patients) and as per label in two patients refractory to oxaliplatin- and irinotecan-based
regimens. In all of these patients, refractoriness to irinotecan and oxaliplatin was defined as documented disease progression during or within 3 to 6 months of receiving an irinotecan- or oxaliplatin-based regimen.

**Cellular Models, Cell Viability, Bromodeoxyuridine, and Apoptosis Assays**

HT-29 and COLO-205 cells were cultured in RPMI 1640-1640 medium, whereas DiFi cells were grown in F-12 (Invitrogen, Carlsbad, CA). DiFi cells were transduced with a lenti-control vector and a lentiviral vector carrying a mutated hBRAF V600E cDNA (a generous gift of Maria S. Soengas, PhD, Ann Arbor, MI). The lentivirus production, cell infection, and transduction procedures have been described elsewhere (Vigna E, Naldini L. J Gene Med 2:308-316, 2000). Cetuximab and panitumumab were obtained from the hospital pharmacy. Sorafenib tosylate was purchased from Sequoia Chemicals (Pangbourne, United Kingdom), dissolved in dimethyl sulfoxide, and stored in aliquots at −20°C. Cells were seeded in 96-well plates and were incubated with drugs at 37°C in 5% carbon dioxide for 72 to 96 hours, after which cell viability was assessed by adenosine triphosphate content using the CellTiter-Glo Luminescent Assay (Promega, Madison, WI). Vehicle- and medium only– containing wells were added as controls. The bromodeoxyuridine assay was used to determine cell proliferation. Measurements were carried out according to the manufacturer’s instructions and terminated 16 hours after addition of the labeling solution, as previously described (Moroni M, Veronese S, Benvenuti S, et al. Lancet Oncol 6:279-286, 2005). Caspase 3/7 activity in cells was used as a measure of apoptosis and was determined using the Caspase-Glo 3/7 assay kit (Promega) following the manufacturer’s instructions. Luminescence was detected using a DTX-880 plate reader (Beckman-Coulter, Fullerton, CA).
BRAF V600E: The V600E is the most common oncogenic mutation of BRAF in cancer. The V600E aminoacid change results in constitutive activation of the BRAF kinase and promotes cell transformation.

PI3K-PTEN-AKT pathway: Signal transduction pathways involving the signaling molecules phosphatidylinositol-3 kinase (PI3K), PTEN and Akt. PI3K generates phosphorylated inositides at the cell membrane which are required for the recruitment and activation of the serine kinase Akt. PTEN is a lipid phosphatase which counteracts the effect of PI3K. Accordingly mutated PI3K and AKT act as dominant oncogenes while PTEN is a tumor suppressor gene.

Cetuximab: Also called Erbitux or C225, cetuximab is a monoclonal antibody that is designed to target EGFR and block its signaling activity by initiating receptor activation.

Panitumumab: Also known as ABX-EGF, panitumumab is a fully human immunoglobulin G2 monoclonal antibody against EGFR and inhibits ligand-induced activation of the EGFR. This antibody is generated from mouse strains engineered to be deficient in mouse antibody production and to produce fully human antibodies.

KRAS: The gene that encodes K-Ras, a protein that is a member of the small GTPase superfamily, in which a single amino acid substitution results in an activating mutation. Alternative splicing gives rise to variants encoding two isoforms that differ in the C-terminal region.

BRAF: BRAF is an isoform of RAF. Raf proteins (Raf-1, A-Raf, B-Raf) are intermediate to Ras and MAPK in the cellular proliferative pathway. Raf proteins are typically activated by Ras via phosphorylation, and activated Raf proteins in turn activate MAPK via phosphorylation. However, Raf proteins may also be independently activated by other kinases.

Sorafenib: A substance belonging to the family of drugs called raf kinase inhibitors and anti-VEGF that is being studied in the treatment of cancer.

MAPK (mitogen-activated protein kinase): MAPKs are a family of enzymes that form an integrated network influencing cellular functions such as differentiation, proliferation, and cell death. These cytoplasmic proteins modulate the activities of other intracellular proteins by adding phosphate groups to their serine/threonine amino acids.

MSI (microsatellite instability): Microsatellites are repeating units of 1–4 DNA base pairs that are distributed widely throughout the genome and have a high degree of repeat length variation in the population. Their length remains stable with cell division and inheritance so they may be used as molecular markers of cell lineage, in population genetic studies or paternity testing. Defects in the genes involved in DNA mismatch repair result in genomic instability that may be detected as MSI, an alteration in the length of the microsatellites from cell to cell.