Primary and acquired resistance of colorectal cancer to anti-EGFR monoclonal antibody can be overcome by combined treatment of regorafenib with cetuximab.

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Dr. Napolitano and all coauthors have no conflicts of interest to declare for the following manuscript.

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Translational Relevance

The introduction in clinical practice of MAbs against the EGFR, such as cetuximab or panitumumab, in combination with chemotherapy has demonstrated therapeutic efficacy in metastatic CRC patients with all RAS wild-type tumors. However, efficacy of these MAbs is limited by development of resistance mechanisms in cancer cells. Activation of alternative signaling pathways, that bypass the EGFR, has been implicated in the resistance to anti-EGFR therapies. Therefore, the blockade of multiple growth factor and receptor pathways could be necessary to increase the efficacy of anti-EGFR monoclonal antibodies. In this study, we have demonstrated that, in human CRC cells with either primary or acquired resistance to cetuximab, the combined treatment with cetuximab and regorafenib induced synergistic anti-proliferative and apoptotic effects and causes significant tumor growth inhibition. This study provides a rationale for evaluating combined treatment with cetuximab and regorafenib as a therapeutic strategy for preventing and/or overcoming cetuximab resistance in mCRC patients.
Abstract

Purpose: In colorectal cancer (CRC) the activation of the intracellular RAS/RAF and PIK3CA/AKT pathways has been implicated in the resistance to anti-epidermal growth factor receptor (EGFR) monoclonal antibodies (MAbs). We have investigated the role of regorafenib, an oral multikinase inhibitor, in combination with cetuximab, an anti-EGFR MAb, to overcome anti-EGFR resistance.

Experimental Design: We have tested, *in vitro* and *in vivo*, the effects of regorafenib in a panel of human CRC cell lines with a *KRAS* mutation (SW480, SW620, HCT116, LOVO, HCT15) or with a *BRAF* mutation (HT29), as models of intrinsic resistance to cetuximab treatment, and in two human CRC cell lines (GEO and SW48), that are cetuximab-sensitive, as well as in their derived cells with acquired resistance to cetuximab (GEO-CR and SW48-CR).

Results: Treatment with regorafenib determined a dose-dependent growth inhibition in all CRC cell lines. The combined treatment with cetuximab and regorafenib induced synergistic anti-proliferative and apoptotic effects in cetuximab-resistant cell lines by blocking MAPK and AKT pathways. Nude mice were injected subcutaneously with HCT116, HCT15, GEO-CR and SW48-CR cells. The combined treatment caused significant tumor growth inhibition. Synergistic antitumor activity of regorafenib plus cetuximab was also observed in an orthotopic CRC model of HCT116 cells. In particular, the combined treatment induced a significant tumor growth inhibition in the primary tumor site (cecum) and completely prevented metastasis formation.

Conclusion: The combined treatment with cetuximab and regorafenib could be a strategy to overcome resistance to anti-EGFR therapies in metastatic CRC patients.
**Introduction**

CRC is one of the leading causes of cancer-related mortality worldwide, with over 1.2 million new cases and 608,700 deaths estimated in 2008 (1). Despite improvements made in screening strategies, a significant number of patients are still diagnosed at late stages of the disease.

In the last decade, the introduction of targeted therapies in clinical practice, in particular of agents targeting the vascular endothelial growth factor (VEGF)-related pathway (bevacizumab and aflibercept) and the EGFR (cetuximab and panitumumab) has changed the therapeutic approach to metastatic CRC patients, with a significant improvement in progression free survival (PFS) and overall survival (OS) (2). Cetuximab and panitumumab are monoclonal antibodies (Mabs) that block the activation of the EGFR and of its downstream intracellular signals, the RAS-RAF-MEK-MAPK and the PTEN-PIK3CA-AKT pathways (3-6). These two drugs are currently approved for the treatment of metastatic CRC patients with all-RAS wild-type tumors. Nevertheless, prognosis remains poor for most of these patients. In fact, the use of these monoclonal antibodies is limited by the presence of pre-existing intrinsic resistance mechanisms or by the ability of cancer cells to acquire resistance. Possible mechanisms for primary and acquired resistance to cetuximab include mutations in the KRAS, BRAF and NRAS genes, secondary mutation (S492R) in the extracellular domain of EGFR, HER2 gene amplification and/or increased HER2 signaling and overexpression of the MET pathway (7-10).

Recently, it has been elucidated that in the resistance to anti-EGFR therapies different growth factors and receptors could be activated in the cancer cell to drive alternative signaling pathways that bypass the EGFR (11,12). Molecular heterogeneity also plays an important role in the context of resistance, by limiting the success of therapies against a single target. Colorectal cancer patients can harbor different gene mutations in distinct tumor lesions, or even within different regions of the same lesion (13). All these alterations could converge on activation of the RAS–MEK–ERK pathway (9,10,14,15). Understanding the biology of such complex gene heterogeneity in tumors is...
necessary for developing rational combination therapies. In fact, blockade of multiple growth factor and growth factor receptor pathways could be needed to increase the efficacy of anti-EGFR targeted therapies (16).

Regorafenib is an oral multikinase inhibitor, that could target three key oncogenic pathways, such as a) cell growth by inhibition of KIT, RET, RAF-1 and BRAF; b) tumor-induced angiogenesis by targeting VEGFR1, 2 and-3, and the tyrosine kinase with immunoglobulin and epidermal growth factor homology domain 2 (TIE2); and c) tumor microenvironment by blocking platelet-derived growth factor receptor-β (PDGR-β) and fibroblast growth factor receptor (FGFR) (17-19). In preclinical studies, regorafenib exhibited antitumor activity in different tumor xenografts (17). Recently, a phase III study showed that regorafenib treatment significantly improved OS and PFS in patients with metastatic CRC who failed all available therapies (20). Thus, both the Food and Drug Administration (FDA) and the European Medicines Agency (EMA) have approved regorafenib for the treatment of such metastatic CRC patients.

In the present study, we have evaluated the efficacy of regorafenib in combination with cetuximab to overcoming resistance to anti-EGFR MAbs by using different human CRC cell models. We have selected five CRC cell lines with KRAS mutations (SW480, SW620, HCT116, LOVO, HCT15) one with BRAF mutation (HT29) and two cell lines with acquired resistance to cetuximab, that were originally obtained in our laboratory (10,14,21) (Supplementary Table 1). We have found that combined treatment with cetuximab and regorafenib induced synergistic anti-proliferative and pro-apoptotic effects by blocking MAPK and AKT pathways in these CRC cell lines. Moreover, a similar synergistic antitumor activity has been confirmed by in vivo subcutaneous and orthotopic CRC xenograft models.
Material and Methods

Drugs. Cetuximab, an anti-EGFR human-mouse chimeric monoclonal antibody, was kindly provided by Merck Serono Italy (Rome, Italy) and it was ready to use. Regorafenib was kindly provided by Bayer Pharma Italy (Milan, Italy). For in vitro applications, regorafenib was dissolved in sterile dimethylsulfoxide (DMSO) and the 10 mM stock solution was stored in aliquots at -20°C. Working concentrations were diluted in culture medium just before each experiment. For in vivo applications, regorafenib was solubilized in 0.5% Tween-80 in sterile Phosphate Buffered Saline (PBS).

Cell Lines. The human HT29, SW620, LOVO, HCT15CRC cell lines were obtained from the American Type Culture Collection (ATTC) (Manassas, VA) and have been authenticated by IRCCS “Azienda Ospedaliera Universitaria San Martino-IST Istituto Nazionale per la Ricerca sul Cancro, Genova” Italy. The human SW48 (catalogue number: HTL99020), SW480 (catalogue number: HTL95025) and HCT116 (catalogue number: HTL99017) CRC cell lines were obtained from IRCCS “Azienda Ospedaliera Universitaria San Martino-IST Istituto Nazionale per la Ricerca sul Cancro, Genova” Italy. The human GEO colon cancer cell line was kindly provided by Dr. N. Normanno (National Cancer Institute, Naples, Italy). GEO-CR and SW48-CR cells were established as previously described (10,14,21). GEO and GEO-CR cell lines were grown in DMEM (Lonza, Cologne, Germany), supplemented with 10% fetal bovine serum (FBS) (Lonza), 1% penicillin/streptomycin (Lonza). SW48, SW480, HCT116, LOVO, HCT15, SW48-CR, cells were grown in RPMI-1640 (Lonza) supplemented with 10% FBS, 1% penicillin/streptomycin. SW620 and HT29 cancer cells were grown in McCoy medium (Lonza) supplemented with 20% FBS (Lonza), 1% penicillin/streptomycin (Lonza). All cell lines were grown in a humidified incubator with 5% of carbon dioxide (CO₂) and 95% air at 37°C. All cell lines were routinely screened for the presence of mycoplasma (Mycoplasma Detection Kit, Roche Diagnostics, Monza, Italy).
**Proliferation Assay.** Cancercell lines were seeded in 24-well plates and were treated with different concentrations of cetuximab (range, 0.001 to 20 µg/ml) alone or in combination with regorafenib (range, 0.001 to 5 µM) for 96 hours. Cell proliferation was measured with the 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide (MTT). The IC$_{50}$ was determined by interpolation from the dose-response curves. Results represent the median of three separate experiments, each performed in quadruplicate. Results of the combination treatment were analyzed according to the method of Chou and Talalay by using the CalcuSyn software programme (Biosoft, Cambridge, UK).

**Apoptosis assay.** HT29, SW480, SW620, HCT116, LOVO, HCT15, GEO-CR and SW48-CR cells were seeded in six-well plates, treated with cetuximab, regorafenib or their combination at different concentrations 72 hours and stained with Annexin V-fluorescein isothiocyanate (FITC) (Invitrogen, CA, USA). Apoptotic cell death was assessed by counting the numbers of cells that stained positive for Annexin V-FITC using an Apoptosis Annexin V-FITC Kit (Invitrogen, CA, USA), coupled with fluorescence-activated cell sorting (FACS) analysis, by following manufacturer’s protocol.

**Immunoblotting.** SW480, SW620, HCT116, LOVO, HCT15, GEO-CR and SW48-CR cells were seeded into 100 mm$^2$ dishes and treated with vehicle, cetuximab, regorafenib, or their combination for 24 hours at different concentration as following indicated. Fifty mg of protein lysates, estimated by a modified Bradford assay (Bio-Rad, Munich, Germany), were subjected to Western blot, as previously described(22), by using the following antibodies: AKT polyclonal antibody (#9272), pAKT monoclonal antibody (#4060), phospho-S6 ribosomal protein (#4856), p44/42 MAPK polyclonal antibody (#9102), phospho-p44/42MAPK monoclonal antibody (#9106) were from Cell Signaling (Beverly, MA, USA). Monoclonal anti-α-tubulin antibody (T8203) was from Sigma Chemical Co. (St. Louis, MO, USA). Goat anti-rabbit IgG and rabbit anti-mouse IgG secondary antibodies were from Bio-rad (Hercules, CA, USA). Immunoreactive proteins were
visualized by enhanced chemiluminescence. (ECL plus, ThermoFisherScientific, Rockford, IL, USA). Each experiment was done intriplicate.

**Tumor xenografts in nude mice.** Four- to six-week old female balb/c athymic (nu+/nu+) mice were purchased from Charles River Laboratories (Milan, Italy). The research protocol was approved and mice were maintained in accordance with the institutional guidelines of the Second University of Naples Animal Care and Use Committee. Animal care was in compliance with Italian (Decree 116/92) and European Community (E.C. L358/1 18/12/86) guidelines on the use and protection of laboratory animals. Mice were acclimatized at the Second University of Naples Medical School Animal Facility for 1 week prior to being injected with cancer cells and then caged in groups of five under controlled conditions (12–12 h light-dark cycle; room temperature 20±2°C; humidity 55–60%). A total number of 3.5 \times 10^6 GEO-CR, SW48-CR cells and 2 \times 10^6 HCT116, HCT15 cells in in 200 µl of matrigel (BD Biosciences, Milan, IT):PBS (1:1) were subcutaneously injected to the dorsal flank of mice. When the mean values of tumors were between 200-300 mm³, mice were randomly assigned to one of the following groups (10 mice per group). Group 1: vehicles administrated orally and intraperitoneally (i.p.). Group 2: cetuximab injected twice a week i.p. at the dose of 1 mg for 3 weeks. Group 3: regorafenib administered by daily oral gavage at the dose of 10 mg/kg for 3 weeks. Group 4: combination of regorafenib and cetuximab. Monitoring of tumor growth was performed until tumors reached approximately 2,000 mm³, when mice were euthanized. Tumor size was evaluated twice a week by calliper measurements using the following formula: \( \pi/6 \times \text{larger diameter} \times (\text{smaller diameter})^2 \). Student's t test was used to evaluate the statistical significance of the results.

**Orthotopic colorectal cancer model.** Four- to six-week old female balb/c athymic (nu+/nu+) mice purchased from Charles River Laboratories (Milan, Italy) were used. The orthotopic implantation was performed as described by Hoffman and colleagues (23). In brief, subcutaneous tumors derived from HCT116 cells were obtained. When tumors reached a mean volume of 500 mm³, animals were
euthanized, the tumors were removed using sterile techniques, divided into 2-3 mm-sized pieces, and harvested in PBS on ice. Mice were treated with antibiotics, ticarcillin (50 mg kg\(^{-1}\)i.v.), two hours before and after tumor implantation. Animals were anesthetized with 2,2,2-tribromoethanol 97% TBE, Avertin (Sigma-Aldrich, St. Louis, MO, USA). TBE solution was prepared fresh daily by mixing 0.625 g of 97% crystalline TBE powder with 25 ml sterile 0.9% saline and then injected intraperitoneally at 0.01 ml/g body mass (250 mg/kg). The abdomen was prepped with betadine solution and the surgical site was isolated in a sterile fashion. A laparotomy of 0.5 cm was conducted; the cecum was exteriorized and isolated using pre-cut, sterile gauze. A warm saline solution was used to keep the cecum wet. Subsequently, the cecum wall was lightly damaged and a single tumor fragment from HCT-116 subcutaneous tumors was sutured to the mesenteric border of the cecum wall using 6.0 nylon surgical sutures. Upon completion, the cecum was placed into the abdominal cavity and the abdominal wound was sutured using a 6.0 Ethicon absorbable stitches (Ethicon Inc., Somerville, NJ). Fourteen days after the injection, mice were randomly assigned to four groups (7 mice for each group) to receive one of the following treatments. Group 1: daily administration of PBS/0.5% Tween 80 by oral gavage for 5 days a week and i.p. injection of PBS twice a week (control group). Group 2: daily administration of diluent for 5 days a week and i.p. injection of cetuximab 1 mg twice a week. Group 3: daily administration of regorafenib 10 mg/kg by oral gavage for 5 days a week and i.p. injection of PBS twice a week. Group 4: combination of oral regorafenib and i.p. cetuximab. Treatment was continued for 3 weeks, and the mice were euthanized 1 week later. The body weights were monitored daily. Primary tumors in the cecum were excised and weighed. The final tumor was measured with a caliper and the volume was calculated by the following formula: \(\pi/6 \times \text{larger diameter} \times \text{(smaller diameter)}^2\). The presence of metastasis was evaluated in the peritoneum, liver, intestines, lungs, rectum, and spleen and confirmed by histologic review. The tumor excised from each mouse was divided into 3 parts. One piece was formalin-fixed; the other two pieces were frozen at -80 C in RNAlater. Hematoxylin and eosin staining confirmed the presence of tumors in each sample.
Results

Sensitivity to cetuximab and regorafenib treatment in a panel of human CRC cell lines.

We first tested in vitro the activity of cetuximab and regorafenib, as single agents, in a panel of human CRC cell lines to characterize their spectrum of activity. We selected eight human CRC (GEO, SW48, HT29, SW480, SW620, HCT116, LOVO, HCT15) cell lines, having different mutation profiles in KRAS, NRAS, BRAF, and PIK3CA genes (Supplementary Table 1). Cancer cells were treated with cetuximab at concentrations ranging from 0.01 to 20 µg/ml and with regorafenib at concentrations ranging from 0.05 to 5 µg/ml for 96 hours. The drug concentrations required to inhibit cell growth by 50% (IC50) were determined by interpolation from the dose-response curves.

Two CRC cell lines were sensitive to cetuximab: SW48, a cell line “quadruple wild type” for KRAS, BRAF, NRAS and PIK3CA genes, and GEO cells with a KRAS codon 12 mutation, with IC50 of 0.5 and 0.1 µg/ml, respectively. Despite GEO cells harbor a KRAS gene mutation, previous studies from different laboratories, including our own, demonstrated that this CRC cell line is one of the most sensitive to the in vitro and in vivo antitumor activity of cetuximab treatment (14,21,24-26). HT29, SW480, SW620, HCT116, LOVO and HCT15 were primarily resistant to cetuximab, as shown in Figure 1. These cells have an activating KRAS gene mutation in either codon 12 or 13 within exon 2, except HT29 cells that have a BRAF mutation (V600E). Cetuximab was also not effective in GEO-CR and SW48-CR cells, two models of cetuximab-acquired resistance, previously obtained in our laboratory (10,14,21). As shown in Figure 1, regorafenib show a different proliferation inhibitory effect in these human CRC cell lines, with IC50 values ranging between 0.5 µM (HCT116, HT29, LOVO), 1 µM (GEO), 2 µM (SW480, HCT15) and >2 µM (SW48, SW620, SW48-CR, GEO-CR). No significantly differences in regorafenib efficacy were observed among CRC cell lines harboring KRAS, NRAS, BRAF, PIK3CA mutations, indicating that its anti-tumor activity seems to be independent of the molecular profile of CRC cell lines tested.
Effects of cetuximab in combination with regorafenib in a panel of human CRC cell lines with primary and acquired resistance to anti-EGFR drugs in vitro.

We evaluated the anti-proliferative activity of cetuximab and regorafenib in combination in the panel of human CRC cell lines. (Supplementary Figure 1 and 2). Combination Index (CI) values were calculated according to the Chou and Talalay mathematical model for drug interactions using the CalcuSyn software, as previously described (10,14,24,27). A synergistic growth inhibitory effect was observed in human CRC cell lines with both primary and acquired resistance to cetuximab. In fact, the CI values for the combined treatments were significantly <1.0 for all the drug doses tested (CI values ranging between 0.0001 and 0.7). (Supplementary Figure 1 and 2). In contrast, an antagonistic effect of the combined treatment was observed in sensitive CRC cell lines (GEO and SW48) with CI values significantly >1.0 (data not shown).

Effects of cetuximab in combination with regorafenib on intracellular signaling pathways in a panel of human CRC cell lines with primary and acquired resistance to anti-EGFR drugs.

To examine the mechanism by which the combined treatment contributes to inhibition of proliferation in CRC cell lines with primary or acquired resistance to anti-EGFR inhibitor, the activation of EGFR downstream signaling molecules was evaluated. SW480, SW620, HCT116, LOVO, HCT15, SW48-CR, and GEO-CR cells were treated with cetuximab, regorafenib and/or their combination. The activation of PIK3CA/AKT and RAS/MAPK pathways was analyzed by Western blotting. The combined treatment with cetuximab and regorafenib substantially inhibited phosphorylation of both AKT and MAPK after 24 hours of treatment compared to single agent treatments (Figure 2). A strong reduction of phosphorylated S6 ribosomal protein (pS6) levels, the major downstream effector of AKT/m-TOR signaling, was observed in the combination treatment (Figure 2). These findings suggested that cetuximab in combination with regorafenib could overcome resistance to anti-EGFR treatment by inhibiting PIK3CA/AKT and MAPK pathways.
Pro-apoptotic effect of cetuximab in combination with regorafenib in CRC cell lines with primary and acquired resistance to anti-EGFR drugs.

We measured the ability of cetuximab and regorafenib as single agents or in combination, to induce apoptosis in CRC cell lines by the Annexin V-FITC assay (Table 1 and Supplementary Figure 3). Compared to single agent, the combined treatment induced significantly early and late apoptosis in the whole panel of human CRC cell lines with primary or acquired resistance to cetuximab.

Cetuximab plus regorafenib combination exhibits antitumor activity in subcutaneous CRC xenografts models.

We evaluated the in vivo activity of cetuximab alone or in combination with regorafenib in nude mice subcutaneously injected with cetuximab-resistant HCT15, HCT116, GEO-CR or SW48-CR cell lines. Mice were randomly assigned to receive vehicle, cetuximab, regorafenib or their combination and were treated for three weeks. As shown in Figure 3, treatment with cetuximab had little or no effect on tumor growth in all tumor xenografts. Similar results were obtained in the groups treated with regorafenib alone. On the contrary, the combined treatment significantly inhibited tumor growth compared both to control group and to single agent treatments in all tumor xenografts (Figure 3). Single agent and combination treatment protocols were well tolerated by mice and were not accompanied by any major side effect or treatment-related weight loss. No cellular abnormalities were observed in the examined organs, including heart, lung, liver, kidney and spleen derived from all xenograft mouse models (data not shown).

Cetuximab plus regorafenib combination inhibits tumor growth in an orthotopic human CRC xenograft.

An orthotopic CRC model with HCT 116 CRC cells was established, as described in Material and Methods. Both cetuximab and regorafenib were well tolerated, and no significant loss of animal weight was observed in the group of combined treatment, whereas a significant weight loss occurred.
in the single agent treatment groups, compared with the mice weight before treatment. The observed weight loss in these groups was probably caused by the presence of growing tumors and peritoneal metastases (Supplementary Figure 4). Of interest combined treatment showed a significant antitumor effect compared to vehicle, cetuximab or regorafenib single agent groups (Figure 4 and Table 2). Mice treated with vehicle had large tumors in the cecum and peritoneum with 100% incidence of regional (mesenteric) lymph node metastases. Mice receiving cetuximab or regorafenib alone had large tumors with 80% and 70% respectively incidence of lymph node metastases. The combined treatment strongly inhibited the tumor growth in the cecum and no peritoneum metastases were observed (Figure 4 and Table 2). The combined treatment was also evident on tumor vascularization. In fact, tumors in mice treated with vehicle, cetuximab or regorafenib were large and highly vascularized, whereas cetuximab plus regorafenib treated mice developed small tumors without evidence of neovascularization. (Figure 4 and Table 2). No liver or lung metastases were detected macroscopically in all groups (data not shown).
Discussion

The development of targeted therapies has provided new options for the personalized management of patients with advanced solid tumors. MAbs directed against the EGFR, such as cetuximab and panitumumab, have emerged as important therapeutic agents in the treatment of metastatic CRC patients. However, their use is substantially limited by intrinsic and acquired cancer cell resistance. Several hypothesis have been developed to explain why resistant cancer cell arises and how it is possible to overcome it. One possibility is cancer intrinsic genetic heterogeneity, which could be more prominent in the metastatic setting (28,29). Heterogeneous genetic alterations in genes involved in the EGFR pathways have been hypothesized to play a role in resistance to anti-EGFR drugs in CRC, including activating mutations in KRAS, NRAS, B-RAF and PIK3CA, and loss of expression of PTEN (13). The overall scenario is complicated by presence of additional genetic mechanisms able to activate the RAS pathway in the absence of molecular alterations affecting RAS or its immediate downstream effectors (30-37). One strategy to overcome the limitations of targeting an individual growth factor receptor such as the EGFR is to combine different drugs that target different growth controlling pathways. In fact, the use of MAbs blocking an individual pathway has been largely limited by the presence of a compensatory feedback loop in another pathways. In our study, in order to circumvent this compensatory feedback, we have tested cetuximab in combination with regorafenib in human CRC cell lines with primary or with acquired resistance to the anti-EGFR MAAb cetuximab. The combined treatment with cetuximab plus regorafenib shows a synergistic antitumor effect both in vitro and in vivo, providing the rational for the clinical development of this combination. These results are consistent with previous reports, which showed that combined inhibition of different growth controlling pathways might potentially exhibit a better therapeutic efficacy compared with inhibition of a single pathway (38-40). In this respect, regorafenib inhibits multiple cell membrane tyrosine kinase receptors that are involved in key processes of cancer development and progression, including angiogenesis (17). Furthermore,
regorafenib antitumor activity could be also due in part by its ability to inhibit RAF serine/threonine kinase (41-43).

We have previously shown that a mechanism of acquired resistance to EGFR inhibitors could be the increased secretion of VEGF, suggesting a key role for tumor-induced angiogenesis in the development of anti-EGFR resistance (21). Moreover, treatment with vandetanib, a dual inhibitor of EGFR and VEGFRs, of human EGFR inhibitor-sensitive CRC cells could delay the onset of cancer cell resistance (21). Bianco et al. have shown that human EGFR-inhibitor resistant cancer cells secrete VEGF and placental growth factor and express VEGFR-1. Treatment with vandetanib significantly inhibits VEGFR-1 activation, cell proliferation and migration in these EGFR inhibitor resistant human cancer cell lines (44). Martinelli et al. have investigated the role of combined treatment with selective anti-EGFR drugs, such as erlotinib or cetuximab, and sorafenib, another multitargeted inhibitor of C-RAF and B-RAF and of all three VEGFRs (3,24). Also in this study the combined treatment determined significant anti-proliferative and anti-migratory effects in vitro and antitumor activity in vivo in xenografts models of human cancer cell lines (24).

In the clinical setting, several studies have explored the possibility of combining anti-EGFR drugs such as cetuximab, panitumumab or erlotinib, with different anti-angiogenic drugs, including bevacizumab or sorafenib. The results in unselected non small cell lung cancer (NSCLC) or CRC patients have been contradictory (45-49). However, the results of a randomized phase II study in 154 advanced NSCLC patients that were selected for the presence of activating EGFR gene mutations have recently demonstrated a statistically and clinically relevant increase in the efficacy of the combined treatment with erlotinib plus bevacizumab compared to single agent standard therapy with erlotinib. Median PFS was significantly longer in the combination arm (16 months) compared to single agent erlotinib arm (9.7 months) (50).

A difficult question to answer is whether combining anti-VEGF and anti-EGFR mAbs antibodies, at least in combination with cytotoxic drug, has definitively proven to be
detrimental, or at least not effective in the first line treatment of metastic CRC. Two large randomize phase III studies have evaluated the efficacy of adding an anti-EGFR monoclonal antibody such as cetuximab (CAIRO-2) or panitumumab (PACCE), to an oxaliplatin-containing chemotherapy doublet plus bevacizumab (48,49). Both studies have shown that the addition of the anti-EGFR mAbs does not improve efficacy. The possibility of a negative interaction between bevacizumab and anti-EGFR antibodies or of a negative interaction when the two antibodies and chemotherapy are combined cannot be ruled out, although no mechanisms behind such potential interactions is known. Although these studies have demonstrated a detrimental effect of the combine treatment of cetuximab with bevacizumab in addition to chemotherapy in metastatic CRC, in our study we have explored the antitumor activity of cetuximab in combination with a different antiangiogenic drug such as regorafenib. While bevacizumab is a monoclonal antibody directed against VEGFA, regorafenib has a broader spectrum of activity blocking different tyrosine kinase receptors, that are potentially involved in the mechanisms of resistance to cetuximab. This may explain the synergistic effect that we have found in this study.

In summary, the present study provides experimental evidence that the combined treatment with anti-EGFR drugs, such as cetuximab, and with a multiple signaling pathway inhibitor, such as regorafenib, could be a potential therapeutic strategy to investigate in a clinical setting for overcoming intrinsic or acquired resistance to EGFR inhibitors in CRC patients.
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Table 1. Pro-apoptotic effects of cetuximab in combination with regorafenib in CRC cell lines with primary and acquired resistance to anti-EGFR inhibitor.

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<td></td>
<td>Combination</td>
<td>48%</td>
<td></td>
<td>Combination</td>
<td>64%</td>
</tr>
<tr>
<td>HCT116</td>
<td>CTR</td>
<td>10%</td>
<td>GEO-CR</td>
<td>CTR</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>Cetuximab</td>
<td>18%</td>
<td></td>
<td>Cetuximab</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>Regorafenib</td>
<td>20%</td>
<td></td>
<td>Regorafenib</td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>Combination</td>
<td>42%</td>
<td></td>
<td>Combination</td>
<td>52%</td>
</tr>
</tbody>
</table>

* The rate of apoptosis was expressed as a percentage of the total cells counted.
Table 2. Cetuximab plus regorafenib combination inhibits growth of orthotopic HCT116 CRC xenografts.

<table>
<thead>
<tr>
<th>TREATMENT GROUP</th>
<th>TUMOR VOLUME (mm$^3$) (%)</th>
<th>CECAL TUMOR WEIGHT (G) (%)</th>
<th>INCIDENCE OF LIMPH NODE METASTASIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTR</td>
<td>15300 - (100%)</td>
<td>5,1 - (100%)</td>
<td>10/10</td>
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<tr>
<td>Cetuximab</td>
<td>13500 - (88%)</td>
<td>4,9 - (82%)</td>
<td>8/10</td>
</tr>
<tr>
<td>Regorafenib</td>
<td>10900 - (71%)</td>
<td>4,2 - (82%)</td>
<td>7/10</td>
</tr>
<tr>
<td>Combination</td>
<td>750 - (4,9%)</td>
<td>1 - (19,6%)</td>
<td>0/10</td>
</tr>
</tbody>
</table>
Figure Legends

Figure 1. Effects of cetuximab and regorafenib treatment on cell proliferation in a panel in a panel of human CRC cell lines.

Cells were treated with different concentrations of cetuximab (range, 0.01 to 20 μg/ml) and regorafenib (range, 0.05 to 5 μg/ml) for 96 hours and evaluated for proliferation by MTT staining, as described in Materials and Methods. The IC₅₀ was determined by interpolation from the dose-response curves. Results represent the median of three separate experiments, each performed in quadruplicate.

Figure 2. Effects of cetuximab in combination with regorafenib on intracellular signaling pathways in a panel of CRC cell lines with primary and acquired resistance to anti-EGFR inhibitor.

Cells were treated with cetuximab at dose of 1 mg/mL, with regorafenib at dose of 1μM) or with their combination for 24 hrs. Total cell protein extracts (50μg) were subjected to immunoblotting with the indicated antibodies, as described in Materials and Methods. Anti-tubulin antibody was used for normalization of protein extract content. Experiments were repeated three times.

Figure 3. Effects of cetuximab in combination with regorafenib on HCT15, HCT116, GEO-CR and SW48-CR tumor xenografts.

Mice bearing xenografts of the human CRC cell line HCT15, the human CRC cell line HCT116, the human CRC cell line GEO-CR, or the human CRC cell line SW48-CR were treated with cetuximab (1 mg/dose twice a week intraperitoneally) and/or regorafenib (10 mg/kg/daily oral gavage) for 3 weeks. Animals were sacrificed when tumors achieved 2,000 mm³ in size. Each group consisted of 10 mice. *** = P<0.0005 (combination versus control).
Figure 4. Cetuximab plus regorafenib combination inhibits growth of orthotopic HCT116 CRC xenografts.

HCT116 cells were injected into the cecal wall of nude mice. Two weeks later, the mice were randomly assigned (7 mice each group) to receive: daily administration of PBS/0.5% Tween 80 by oral gavage for 5 days a week and i.p. injection of PBS twice a week (control); daily administration of diluent for 5 days a week and i.p. injection of cetuximab 1 mg twice a week; daily administration of regorafenib 10 mg/kg by oral gavage for 5 days a week and i.p. injection of PBS twice a week; combination of oral regorafenib and i.p. cetuximab. The treatment continued for 3 weeks, and 1 week later mice were killed and necropsied.
Figure 1

**Cetuximab (μg/ml)**

- GEO
- SW48
- HT29
- SW480
- SW620
- HCT116
- LOVO
- HCT150
- SW48-CR
- GEO-CR

**% of cell proliferation**

- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100
- 110

**Regorafenib (μM)**

- GEO
- SW48
- HT29
- SW480
- SW620
- HCT116
- LOVO
- HCT150
- SW48-CR
- GEO-CR

**% of cell proliferation**

- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100

Research.
Figure 3

Tumor volume (mm$^3$) vs. weeks for different cell lines:

- **HCT16**
- **HCT15**
- **SW48-CR**
- **GEO-CR**

The graphs show the growth of tumor volume over 16 weeks for each cell line under various treatments, indicated by different colored lines:

- CTR
- Cetuximab
- Regorafenib
- Cet + Regorafenib

Significant differences are indicated by ***.
Figure 4

<table>
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<th>Combination</th>
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<td><img src="image4.png" alt="Combination Image" /></td>
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Primary and acquired resistance of colorectal cancer to anti-EGFR monoclonal antibody can be overcome by combined treatment of regorafenib with cetuximab

Stefania Napolitano, giulia martini, barbara rinaldi, et al.

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