Molecular Pathways: Fibroblast Growth Factor Signaling: A New Therapeutic Opportunity in Cancer

A. Nigel Brooks, Elaine Kilgour, and Paul D. Smith

Abstract

The fibroblast growth factor/fibroblast growth factor receptor (FGF/FGFR) signaling axis plays an important role in normal organ, vascular, and skeletal development. Deregulation of FGFR signaling through genetic modification or overexpression of the receptors (or their ligands) has been observed in numerous tumor settings, whereas the FGF/FGFR axis also plays a key role in driving tumor angiogenesis. A growing body of preclinical data shows that inhibition of FGFR signaling can result in antiproliferative and/or proapoptotic effects, both in vitro and in vivo, thus confirming the validity of the FGF/FGFR axis as a potential therapeutic target. In the past, development of therapeutic approaches to target this axis has been hampered by our inability to develop FGFR-selective agents. With the advent of a number of new modalities for selectively inhibiting FGF/FGFR signaling, we are now in a unique position to test and validate clinically the many hypotheses that have been generated preclinically.

Background

Fibroblast growth factors (FGF) and their receptors (FGFR) tightly regulate key cell behaviors, such as proliferation, differentiation, migration, and survival, and are fundamental to embryonic development, regulation of angiogenesis, and wound healing in adults. Dysregulation of the FGF/FGFR signaling pathway has been associated with numerous tumor settings, whereas the FGF/FGFR axis also plays a key role in driving tumor angiogenesis.

FGFs and their receptors

The FGF family comprises 18 secreted ligands, which can be divided into 2 subfamilies: the hormone-like FGFs (FGF19, 21, and 23) and the canonical FGFs (FGF1–10, 16–18, and 20; ref. 1). FGFs are readily sequestered to the extracellular matrix by heparan sulfate proteoglycans (HPSG). For signal propagation, FGFs are released from the extracellular matrix by proteases or specific FGF-binding proteins, which in turn are important negative regulators that lead to a conformational shift in the FGFR structure, thereby disrupting downstream signaling. FGF signaling pathways (Fig. 1; ref. 5). Other pathways can also be activated by FGFRs, including STAT-dependent signaling pathways. For example, FGF induces SPRoutY (SPRY) proteins, which in turn are important negative regulators that bind to growth factor receptor–bound protein 2 (GRB2), thereby disrupting downstream signaling. FGF signaling also induces proteins such as MAPK phosphatase 3 (MKP3) and Similar Expression to FGF (SEF) that either compete for binding to their cognate FGFR (2).

FGF/FGFR signaling

Dimerization of the ternary FGF:FGFR:HPSG complex leads to a conformational shift in the FGFR structure, resulting in intermolecular transphosphorylation of the intracellular tyrosine kinase domain and carboxy-terminal tail (3). There are 5 FGFRs, of which 4 (FGFRs 1–4) are highly conserved single-pass transmembrane tyrosine kinase receptors (3). The extracellular regions of these receptors comprise 3 immunoglobulin (Ig)–like domains (I–III). IgII and IgIII form the FGF ligand-binding site, with an acidic, serine-rich region located between IgI and IgII (the acid box; ref. 4). FGFRs 1 to 3, but not FGFR4, are subject to alternate splicing in IgIII, creating Ib and Ic variants with differing ligand-binding specificities that are expressed in a tissue-specific manner (3). The intracellular region of FGFRs 1 to 4 contains a juxtamembrane split kinase domain, which contains the classical tyrosine kinase motifs and a carboxy-terminal tail (3). The fifth receptor, FGFR5, can bind FGFs with high affinity but lacks the intracellular tyrosine kinase domain, and its role is less well understood (5).

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doi: 10.1158/1078-0432.CCR-11-0699

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substrate binding or cause receptor dephosphorylation (6).

Other molecules have been identified that can attenuate signaling, including the cell-surface molecules N-CAM and N-cadherin and the sprouty-related enabled/vasodilator-stimulated phosphoprotein homology 1 domain-containing protein (5).

From this brief overview, it is clear that the FGF/FGFR signaling pathway is multifactorial and complex. It has evolved in a way that subserves the many different biologic functions of FGFs that occur in a tightly regulated temporal and spatial manner throughout development and in adult life.

**Mechanisms of oncogenic FGF/FGFR signaling**

It has long been recognized that FGFRs are overexpressed in many cancer cell types. Our understanding of the
mechanisms by which FGFR signaling is dysregulated and drives cancer has increased significantly in recent years. Arguably, the most compelling of these mechanisms involve genetic lesions in FGFRs that, in some cases, define FGFRs as bona fide oncogenes to which tumors cells are addicted (7). The mechanisms of dysregulation are briefly summarized below and depicted in Fig. 1B.

**Activating mutations**

FGFR mutations that confer constitutive activation have been described in a number of congenital skeletal disorders (5). FGFRs have been identified as among the most commonly mutated kinase genes in human cancers, with mutations in FGFR2 and FGFR3 being most prevalent (5). For example, approximately 50% to 60% of nonmuscle invasive and 17% of high-grade bladder cancers possess FGFR3 mutations that cause constitutive FGFR dimerization and activation (8). Activating and oncogenic FGFR2 mutations located in the extracellular and kinase domains of the receptor have been described in 12% of endometrial carcinomas (9). Importantly, the FGFR2 mutations found in endometrial cancer confer sensitivity to FGFR inhibition (9). More recently, FGFR2 mutations have been described in 5% of squamous non–small cell lung cancers (NSCLC; ref. 10), although full validation of these as activating mutations has not been reported. FGFR3 mutations in bladder cancer and FGFR2 mutations in endometrial cancer are mutually exclusive with mutations in HRAS and KRAS, respectively. In addition, mutations in the FGFR4 kinase domain have been found in the childhood soft tissue sarcoma rhabdomyosarcoma, causing autophosphorylation and constitutive signaling (11).

**FGFR gene amplification**

FGFR gene amplification often leads to FGFR overexpression, which can provoke ligand-independent signaling. In breast cancer, amplification of the genomic locus of FGFR1 (8p11–12) occurs in approximately 10% of predominantly estrogen receptor (ER)–positive patients (12). In vitro studies support the potential oncogenic nature of FGFR1 amplification (13); however, due to the gene-dense nature of the 8p11-12 amplicon in breast cancer, there is continuing debate about the identity of the driving oncogene. More recently, FGFR1 has been found to be amplified in 22% of squamous NSCLC (14), and these amplifications seem to confer dependence upon FGFR signaling. Unlike the broad amplicon containing FGFR1 found in breast cancers, the amplicon in lung is more focal; it remains to be seen if these differences influence the degree of addiction to FGFR1. FGFR2 amplifications have been reported in up to 10% of gastric cancers, most of which are diffuse-type with relatively poor prognosis (15). Further, in an FGFR2-amplified gastric cancer cell line, Snu-16, FGFR2 downregulation led to significant inhibition of cell growth and survival that further translated into tumor growth regression in vivo (16). In some gastric cancer cell lines, FGFR2 amplification is accompanied by deletion of the coding exon located proximal to the C-terminus (17). This deletion impedes receptor internalization, thereby contributing to constitutive activation of the receptor. The presence of FGFR2 gene amplifications in gastric cancer is associated with sensitivity to inhibition of FGFR signaling by tyrosine kinase inhibitors and monoclonal antibodies in preclinical models (18, 19).

**Chromosomal translocations**

Several FGFR translocations have been identified in hematologic malignancies, whereby chromosomal rearrangement results in a protein fusing to the kinase domain of an FGFR. Fusion proteins are located in the cytosol, do not undergo lysosomal degradation, are not susceptible to feedback inhibition, and are permanently dimerized in the absence of ligand. Consequently, these translocations lead to FGFR3 overexpression, permanent dimerization of the fusion protein–FGFR complex, and continuous signaling. The mechanism of proliferation is dependent on the type of fusion protein and seems to be disease specific (20). A t(4;14) intergenic translocation, bringing FGFR3 and the adjacent Multiple Myeloma SET domain (MMSET) gene under the control of the Ig heavy chain (IGH) promoter, has been identified in 10% to 20% of multiple myelomas and is associated with poor prognosis and dependence upon FGFR signaling (21, 22). FGFR3 translocations are rarely found in prodromal conditions of multiple myeloma, implicating these translocations in the conversion to full multiple myeloma.

**Autocrine and paracrine signaling**

Although many of the mechanisms discussed so far are the result of genetic dysregulation of the FGF/FGFR signaling axis, ligand-dependent signaling is also likely to play a key role in cancer development. Autocrine FGFR overproduction has been reported in many tumor types (5). In vitro studies have shown that FGF5 overexpression has been associated with a number of tumor cell lines (lung, esophagus, melanoma, colon, and prostate; ref. 23), and in hepatocellular carcinomas (HCC), the upregulation of FGFR2, 8, 17, and 18 initiates autocrine growth stimulation, cell survival, and neoangiogenesis (24–27). Further, HCC has been found to develop in transgenic mice overexpressing the hormonal FGF19 (28), and FGF19 is found on an amplicon on chromosome 11q that also invariably contains the adjacent FGF3, FGF4, and Cyclin D1 (CCND1) genes. This amplicon is found in various diseases, including head and neck squamous cell carcinoma, breast cancer, and squamous NSCLC. Although there is uncertainty about the key oncogenic gene on this amplicon or a presumption that it is CCND1, genetic knockdown of FGF19 inhibits the growth of HCC cell lines carrying the amplicon (29). Autocrine FGFR–FGF2 feedback loops have also been reported in NSCLC cell lines and in human melanomas grown as subcutaneous tumors in nude mice (30, 31).

Paracrine production of FGFs has also been reported in multiple tumor types. High levels of serum FGF2 have been observed in small cell lung cancer and are associated with a poor prognosis (32), possibly because of an FGFR-mediated cytoprotective effect, whereby the expression of
antiapoptotic proteins are upregulated, promoting resistance to current anticancer treatments (33). Increased paracrine expression of one or more of FGF1, 2, 4, 5, 8, and 18 has been found to promote tumor neoangiogenesis in preclinical models via the main endothelial FGFRs, FGFR1 and 2 (34). Poor prognosis has been associated with neoangiogenesis in ovarian cancer and melanomas (35).

**Altered FGFR splicing**

In addition to overexpression of FGFs, altered gene splicing of FGFRs is another mechanism by which ligand-dependent signaling is upregulated. Altered FGFR splicing can allow tumor cells to be stimulated by a broader range of FGFs than would be capable under normal physiologic conditions (36). Altered splicing of the IgIII domains in FGFRs 1, 2, and 3 can switch receptor binding affinity in cancer cells towards FGFs found in the healthy stroma, creating an aberrant paracrine signaling loop (37). In bladder and prostate cancer cell lines, a switch from the FGFR2-IIIb isoform to the IIIc isoform has been associated with resistance to current anticancer treatments (33).

**Other Mechanisms of Oncogenic FGF/FGFR Signaling**

In addition to the predominant mechanisms of FGF/FGFR dysregulation summarized above, several other mechanisms have been identified that may also contribute to cancer development.

**Germline single-nucleotide polymorphisms**

Genome-wide association studies have identified several single nucleotide polymorphisms (SNP) located within FGFR1 intron 2 that are associated with an increased risk of breast cancer (38). Due to the strong linkage disequilibrium between these SNPs, it remains unclear which are mechanistically important, although one of these SNPs (rs2981582) has been reported to be more strongly linked to the development of ER-positive rather than ER-negative breast cancer (39). An SNP located within FGFR4 causing a G388R substitution has been associated with poor prognosis following the onset of cancer (40). The arginine substitution increases receptor stability and induces a migratory phenotype resulting in a more aggressive behavior in multiple cancer types, including breast cancer, colon cancer, and lung adenocarcinoma.

**Dysregulation of signal attenuation**

Increased FGF/FGFR signaling can also result from impairment of the normal attenuation and negative feedback steps. Mutations in proteins involved in FGFR internalization can cause increased or prolonged signaling (41). Mutations causing alterations in the structure of FGFRs may also prevent efficient internalization and degradation of the receptors; the FGFR3 G380R substitution identified in bladder cancer increases recycling of the receptor, thereby escaping degradation and resulting in signal prolongation (42). In a splice variant of FGFR2 found to be overexpressed in several cancer cell lines, deletion of the C-terminal tail, including an endocytic motif, contributes to inefficient signal downregulation (43). Loss of expression of negative regulators, including SPRY1, SPRY2, and SEF, has been associated with increased FGE/FGFR signaling in a number of cancers, including prostate and breast cancer (5).

Overall, a consistent finding from these preclinical studies is that dysregulation of FGFR-dependent signaling can contribute to tumor growth and angiogenesis through a variety of mechanisms. These insights have spurred further investigation of the FGE/FGFR pathway as a potential therapeutic target.

**Clinical–Translational Advances**

On the basis of the evidence for their dysregulation in human cancers, several approaches are being pursued to generate agents to disrupt FGF-ligand/receptor activity, including small-molecule tyrosine kinase inhibitors, monoclonal antibodies, and FGF-ligand traps.

**Small-molecule tyrosine kinase inhibitors**

Several companies have generated small-molecule tyrosine kinase inhibitors targeting the intracellular tyrosine kinase domain of FGFRs. The most clinically advanced of these are mainly mixed kinase inhibitors, including brivanib, dovitinib, lenvatinib, ponatinib, and nintedanib (Table 1), with dominant anti-VEGF receptor (VEGFR) and/or anti–platelet-derived growth factor receptor (PDGFR) pharmacology. Activity of most of these agents against FGFRs is weak. Although the broader specificity of these compounds could add to efficacy, the inhibition of several tyrosine kinases will likely result in increased side effects, which may limit the ability to achieve doses required for effective FGFR inhibition. Recently, a phase II trial of the mixed VEGFR/FGFR inhibitor dovitinib in FGFR1-amplified and nonamplified metastatic breast cancer failed to reach its primary endpoint of improved overall response rate, although it was reported that activity was observed primarily in the subgroup of patients with FGFR1 gene amplification (44). The implications of this result for the therapeutic potential of FGFR inhibition in FGFR1 gene amplified breast cancer will remain uncertain until more selective FGFR inhibitors are tested in this setting.

The second-generation compounds are potent FGFR inhibitors with a greater margin for selectivity versus VEGFR and other tyrosine kinases. The first of these have now entered early clinical development: AZD4547 (AstraZeneca; ref. 45); BGJ398 (Novartis; ref. 46); and LY2874455 (Eli Lilly; ref. 18). In vitro studies show that AZD4547 and BGJ398 are more potent inhibitors of FGFR1, FGFR2, and FGFR3 than FGFR4, whereas LY2874455 is a pan-FGFR inhibitor (18, 45, 46). In contrast to VEGFR inhibitors, efficacious doses of AZD4547 and LY2874455 do not induce elevations in blood pressure in several tumor xenograft models, including lung, gastric, multiple myeloma, and bladder cancers (18, 45). All 3 agents have shown antitumor activity in xenograft models with FGFR dysregulation, including
KMS11 and OPM-2 (FGFR3 chromosomal translocation/mutation multiple myeloma); SN1116 (FGFR2-amplified gastric cancer); and RT112 (FGFR3 high-expressing bladder cancer; refs. 16, 18, 45, 46). Preclinical evidence not only suggests that these compounds have potential as cancer therapies but also indicates the need to identify those patient populations most likely to benefit from therapy based on the presence of tumor FGFR mutations or gene amplification and FGFR expression levels. Currently, AZD4547 is being tested in phase I clinical trials in FGFR1 and FGFR2 gene–amplified patients (NCT00979134) and in phase IIa trials in FGFR2 gene–amplified gastric cancer and FGFR1 gene–amplified ER-positive breast cancer (NCT01457846 and NCT01202591, respectively), whereas BGJ398 is being tested in phase I trials in solid tumors with FGFR1 and FGFR2 gene amplification or FGFR3 mutation (NCT01004224), and LY2874455 is in phase I trials in an unselected cancer patient population (NCT01212107).

Given the broad expression of FGFRs and their key role in development and physiology, toxicity issues are to be expected from FGFR inhibition. The FGFR pathway is involved in normal phosphate and vitamin D homeostasis, and preclinical development of FGFR inhibitors has been complicated by hyperphosphatemia-mediated tissue calcification, owing to blockade of FGF23 release from bone and of the FGF23 signal in kidney (47). FGF23 binds FGRF4 and the IIIc isoforms of FGFR1 and FGFR3 (2, 48), but uncertainty remains about the relative contribution of individual FGFR subtypes to hyperphosphatemia (49–52). In preclinical models, FGFR inhibition results in dynamic modulation of circulating FGF23 levels, with suppressed levels observed during periods of drug exposure (attributable to direct inhibition of FGF23 release from bone) and elevated levels upon drug withdrawal (driven by increased plasma phosphate and vitamin D levels acting on bone to stimulate FGF23 production; ref. 53). Hence, modulation of circulating FGF23, together with elevated vitamin D levels, and the incidence of hyperphosphatemia are potential biomarkers for effective FGFR inhibition. The challenge for specific FGFR inhibitors in the clinic is to determine a therapeutic dose that will balance efficacy against gene-addicted tumors with a manageable tolerability profile.

### Table 1. Current clinical development status of FGF/FGFR-targeting anticancer agents

<table>
<thead>
<tr>
<th>Compound</th>
<th>Company</th>
<th>Target</th>
<th>Clinical development (indication)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brivanib</td>
<td>Bristol-Myers Squibb</td>
<td>FGFR, VEGFR</td>
<td>Phase III (CRC, HCC, liver)</td>
</tr>
<tr>
<td>Dovitinib</td>
<td>Novartis</td>
<td>FGFR, PDGFR, VEGFR, FLT3, c-KIT</td>
<td>Phase III (RCC)</td>
</tr>
<tr>
<td>Lenvatinib</td>
<td>Eisai</td>
<td>FGFR, PDGFR, VEGFR</td>
<td>Phase III (melanoma, thyroid)</td>
</tr>
<tr>
<td>Masitinib</td>
<td>AB Science</td>
<td>FGFR3, PDGFR, c-KIT</td>
<td>Phase III (GIST, melanoma, MM, pancreatic)</td>
</tr>
<tr>
<td>Nintedanib</td>
<td>Boehringer Ingelheim</td>
<td>FGFR, PDGFR, VEGFR</td>
<td>Phase III (NSCLC, ovarian)</td>
</tr>
<tr>
<td>Pazopanib</td>
<td>GlaxoSmithKline</td>
<td>FGFR1, FGFR3, VEGFR, PDGFR, c-KIT</td>
<td>Phase III (breast, lung, ovarian, RCC, STS)</td>
</tr>
<tr>
<td>PI-88</td>
<td>Progen</td>
<td>FGFR1, FGFR2, VEGF</td>
<td>Phase III (HCC, liver)</td>
</tr>
<tr>
<td>Regorafenib</td>
<td>Bayer</td>
<td>FGFR, PDGFR, VEGFR, c-KIT, RET</td>
<td>Phase III (GIST, CRC)</td>
</tr>
<tr>
<td>TSU 68</td>
<td>Pfizer</td>
<td>FGFR, KDR, PDGFR, VEGFR2</td>
<td>Phase III (HCC)</td>
</tr>
<tr>
<td>ENMD-2076</td>
<td>Entremed</td>
<td>FGFR1, KDR, FGFR2, PDGFR, VEGFR, FLT3, c-KIT, Aurora K, FLT3</td>
<td>Phase II (ovarian)</td>
</tr>
<tr>
<td>Ponatinib</td>
<td>Ariad</td>
<td>FGFR, PDGFR, VEGFR</td>
<td>Phase II (AML, CML)</td>
</tr>
<tr>
<td>E3810</td>
<td>Eisai</td>
<td>FGFR1, VEGFR</td>
<td>Phase I (solid tumors)</td>
</tr>
<tr>
<td>PBI-05204</td>
<td>Phoenix Bio</td>
<td>FGFR2, AKT, NF-xB, p70S6K</td>
<td>Phase I (solid tumors)</td>
</tr>
</tbody>
</table>

**Small-molecule tyrosine kinase inhibitors: FGFR selective**

| AZD4547 | AstraZeneca | FGFR1-3 | Phase II (breast, gastric) |
| BGF398 | Novartis | FGFR1-3 | Phase I (solid tumors) |
| LY2874455 | Eli Lilly | FGFR1-4 | Phase I (solid tumors) |

**FGFR antibodies**

| RG7444 | Roche | FGFR3 | Phase I (MM) |

**FGF-ligand traps**

| FP-1039 | Five Prime Therapeutics | FGF1, FGF2, FGF4 | Phase II (endometrial) |

**Abbreviations:** AML, acute myeloid leukemia; CML, chronic myeloid leukemia; CRC, colorectal cancer; FLT3, fms-like tyrosine kinase receptor-3; GIST, gastrointestinal stromal tumor; KDR, kinase insert domain receptor; MM, multiple myeloma; RCC, renal cell carcinoma; RET, REarranged during Transfection; STS, soft tissue sarcoma.

Monoclonal antibodies

Therapeutic monoclonal antibodies are being developed in the hope of delivering agents highly specific for a particular FGF ligand or FGFR isoform, thus improving the side-effect profile associated with inhibition of multiple FGFR isoforms. Antibodies can offer the additional advantage of recruiting the immune system to contribute to the antitumor activity via antibody-dependent cellular cytotoxicity or complement-dependent cytotoxicity (54). Several anti-FGFR monoclonal antibodies have been assessed in preclinical studies. GP369 (Aveo) and HuGAL-FR21 (Galaxy) anti-FGFR2 monoclonal antibodies have shown efficacy in mouse xenograft models of FGFR2-amplified gastric cancer (SNU16) and breast cancer (MFM-223; refs. 19, 55). Antibodies raised against FGFR3 have been shown to be efficacious in the KMS11 (t(4;14) translocated multiple myeloma model and in the RT112 bladder cancer model (22). Recently, a humanized anti-FGFR4 monoclonal antibody was reported to inhibit tumor growth in the HUH7 HCC xenograft model (56), and antibodies against the FGFR4-ligand FGF19 have shown efficacy in preclinical models of colorectal cancer and HCC (57). Little information is available on the tolerability profile of any of these agents. Administration of an anti-FGFR1-I-ligand antibody resulted in profound weight loss in preclinical in vivo models (58), and this has prevented evaluation of its efficacy. The first FGFR antibody to enter clinical development is the anti-FGFR3 antibody MFGFR1877S (Genentech) currently in phase I trials in t(4;14) translocated multiple myeloma patients (NCT01122875). Continued clinical research may identify which FGFR isoforms have the greatest efficacy potential and whether inhibition of particular isoforms can avoid side effects associated with broad specificity small-molecule FGFR inhibitors.

FGF-ligand traps

Another approach for inhibiting FGF:FGFR signaling is by using a ligand trap to sequester FGF ligand and thus preventing it from binding to FGFRs. FP-1039 (Five Prime Therapeutics, Inc.) is a soluble fusion protein consisting of the extracellular FGFR1-I-ligand domain fused to the Fc portion of IgG1 that prevents the binding of FGF1, FGF2, and FGF4 to their associated FGFRs (59). A key question is whether this agent sequesters the hormonal FGFRs, including FGFR3; if not, its use could potentially avoid the hyperphosphatemia side effects observed with small-molecule FGFR inhibitors. FP-1039 is currently being evaluated in a phase II trial in patients with endometrial cancers carrying specific FGFR2 mutations (NCT01244438).

Conclusions

Disregulation of FGF signaling in cancer is now well understood, and it is becoming increasingly likely that certain tumors become dependent on activation of this pathway for their growth and survival. FGF/FGFR dependence offers the hope of developing new therapeutic approaches that selectively target the FGF/FGFR axis in patients whose tumors are known to harbor FGF/FGFR dysregulation. This research fulfills the ambition of many: to treat the right patient with the right drug for the right target. However, there are significant challenges in developing such an approach, not the least of which is the fact that the FGF/FGFR signaling axis is so intimately involved in many normal biologic processes that will also be disturbed by therapeutic intervention. Additionally, it is currently far from clear how to select patients whose tumors are likely to respond to inhibitors of FGF/FGFR signaling. Overcoming these challenges will require considerable focused effort in the coming years if we are to successfully develop this new therapeutic opportunity in cancer.

Disclosure of Potential Conflicts of Interest

A. Nigel Brooks, E. Kilgour, and P.D. Smith are employees of and hold shares in AstraZeneca.

Acknowledgments

Writing support was provided by Zoe van Helmond PhD from Mudskipper Bioscience, funded by AstraZeneca.

Received January 21, 2018; accepted February 15, 2012; published OnlineFirst March 2, 2012.
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Clin Cancer Res  Published OnlineFirst March 2, 2012.

Updated version
Access the most recent version of this article at:
doi:10.1158/1078-0432.CCR-11-0699

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