Molecular Pathways: Adaptive Kinome Reprogramming in Response to Targeted Inhibition of the BRAF–MEK–ERK Pathway in Cancer

Gary L. Johnson, Timothy J. Stuhlmiller, Steven P. Angus, Jon S. Zawistowski, and Lee M. Graves

Abstract

The central role of the BRAF–MEK–ERK pathway in controlling cell fate has made this pathway a primary target for deregulated activation in cancer. BRaf is activated by Ras proteins allowing Ras oncogenes to constitutively activate the pathway. Activating BRaf mutations are also frequent in several cancers, being the most common oncogenic mutation in thyroid carcinoma and melanoma. There are currently two inhibitors, vemurafenib and dabrafenib, approved for treatment of malignant melanoma having activating BRaf mutations. Concurrent administration of BRAF and MAP–ERK kinase (MEK) inhibitor (trametinib) is significantly more active in patients with BRAF-mutant melanoma than either single agent alone, but progression to resistance ultimately occurs by different mechanisms that increase the activation of extracellular signal–regulated kinase (ERK). Such adaptive changes in tumor cell signaling networks allow bypass of targeted oncoprotein inhibition. This is true with targeted inhibitors for BRaf and MEK as well as specific inhibitors for AKT, mTOR, and many receptor tyrosine kinases such as EGF receptor (EGFR) and HER2. It is this adaptive response to targeted kinase inhibitors that contributes to the failure of single-agent kinase inhibitors to have durable responses. This failure is seen in virtually all cancers treated with single-agent kinase inhibitors, most of which are not as dependent on a single signaling pathway such as BRaf–MEK–ERK in melanoma. Thus, understanding the breadth of adaptive reprogramming responses to specific targeted kinase inhibition will be critical to develop appropriate combination therapies for durable clinical responses.

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Background

Two of the major signaling systems controlling proliferation and survival of cells are the mitogen-activated protein kinase (MAPK) and phosphoinositide 3-kinase (PI3K)–AKT signaling networks (1–4). Hence, oncogenic mutations, amplifications, and deletions targeting component proteins and regulators of these two pathways are common in many cancers. Development of inhibitors for key enzymes in these two pathways has progressed rapidly and several inhibitors targeting the MAPK network have shown remarkable clinical response in patients with melanoma. Even though these inhibitors can be initially highly effective in eliciting a clinical response, progression to resistance ultimately occurs. This adaptive response involves reprogramming of the kinome to effectively bypass inhibition of the targeted kinases. Cellular mechanisms involving adaptive changes of the kinome in response to inhibitors of the MAPK network is the topic of this Molecular Pathways review.

The prototypical three-tiered MAPK pathway is composed of a MAP3kinase (MAP3K), MAP–ERK kinase (MEK), and extracellular signal–regulated kinase (ERK; refs. 5, 6). There are multiple MAP3Ks capable of phosphorylating and activating MEK1 and 2 proteins, both of which phosphorylate and activate ERK1 and 2. MAP3Ks that phosphorylate and activate MEK1/2 include Raf1, BRaf, MAP3K1 (MEKK1), and MAP3K8 (Tpl2/COT; Fig. 1). This occurs on two serines in an identical peptide sequence in the activation loop of both MEK1 and 2, making the activation of these kinases indistinguishable by most techniques. In specific cancers, BRaf has been found to be mutated, amplified, or have altered splicing, leading to increased kinase activity. Raf1, MAP3K1, and MAP3K8 have also been found to be mutated or altered in expression in specific cancers [see The Cancer Genome Atlas (TCGA) Data Portal; ref. 7].

MAPK substrates and cellular functions

Functionally, ERK1 and 2, the MAPKs downstream of these MAP3Ks and MEK1 and 2, have multiple substrates that control transcription, translation, cell cycle, and cell survival (8–10). Although a plethora of targets have been reported (9), a much smaller number have been sufficiently validated. Recent proteomics analyses have contributed...
extensively to our identification of these substrates (11–13). A few representative ERK target substrates relevant to cancer phenotype are shown in Fig. 1.

A principal focus has been on characterizing nuclear targets for ERK1/2 because of its well-observed translocation to the nucleus. The list of transcription factors phosphorylated by ERK1/2 is large and includes Myc, Elk1, Ets1, Fos, SP1, and others (9, 14). ERK-mediated phosphorylation seems to stabilize short-lived transcription factors (i.e., Myc and Fos) and assist in the formation of higher order complexes necessary for transcriptional regulation (i.e., Elk1, Ets1, and Fos; refs. 14, 15). Interestingly, recent proteomic experiments, performed in the presence or absence of MEK inhibitors, revealed a role for ERK-mediated phosphorylation in the regulation of JunB (12). Hence, activation of the MEK–ERK pathway also contributes to the formation and regulation of AP1 complexes (16). A large-scale analysis of ERK2 substrates also identified an unexpected importance of ERK2 in regulating ETV3, an Ets repressor whose repressive activity was reversed by ERK-catalyzed phosphorylation of ETV3 (10).

Not surprisingly, the transcriptional targets regulated by MEK–ERK signaling are also broad and include many genes whose functions are deregulated in cancer. This includes immediate early genes that are activated in response to MEK–ERK signaling (17). Prolonged activation of ERK1/2 or loss of feedback inhibition perturbs the normal transient activation of these events and contributes to cancer progression. For example, the MAPK phosphatases (DUSPs) and Sprouty (SPRY) are involved in negative feedback regulation of MAPK and growth factor–regulated signaling by receptor tyrosine kinases such as the EGF receptor (EGFR;
mutations occurring in melanoma and thyroid carcinoma are common. Activating BRaf mutations are the most frequent activating mutations in components of the pathway are proliferation and transformation (25, 28, 30, 31). Hence, ERK signaling network is a major oncogenic driver of fied in primary tumors compared with BRaf.

Significantly to the enhanced activation state of the pathway. Breast cancer (33, 34). Such amplifications can contribute approximately 31% of basal triple-negative breast cancers of these genes. For example, BRaf is amplified in previous sequencing studies did not find activating muta-
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The ERK-mediated phosphorylation of paxillin regulates an important scaffold for localizing other kinases (FAK) and GTPases (Rac) to focal adhesions (22, 23). The “downstream” phosphorylation and activation of additional kinases (Rsk, Msks, and Mnk) allows these kinases to further regulate cell survival and protein translation processes in an ERK-dependent mechanism (24). Negative feedback regulation of “upstream” kinases in the MAPK network (Raf, Pak, KSR, and MEK1/2) also plays an essential function in determining signaling magnitude and duration through the ERK pathway (19, 20, 25). Thus, ERK1/2-regulated phosphorylation of these numerous substrates regulates many critical regulatory functions in the cell.

MAPK signaling in cancer

BRaf is a MAP3K coupled strongly with receptor tyrosine kinase–driven MEK–ERK activation. Raf proteins are activated by GTP-bound Ras (26, 27), thus oncogenic Ras proteins activate BRAF and the MEK–ERK pathway (26). BRAF is mutated in approximately 50% of metastatic melanomas, 55% of advanced thyroid carcinomas, and in a lower proportion of colorectal, ovarian, and lung carcinomas (7, 28–32). TCGA is rapidly expanding the tumor genomic land-

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Clinical–Translational Advances

Activated ERK has a complex feedback regulation of several components in the MAPK signaling network (Fig. 1). This feedback regulation involves ERK phosphorylation of specific receptor tyrosine kinases such as EGFR, Son of Sevenless 1 (SOS), which is a Ras guanine nucleotide exchange factor, Raf1, BRaf, and MEK1. ERK phosphorylation of each of the proteins decreases their activity, effectively suppressing the activation of ERK. NF1, a Ras GTPase-activating protein, is phosphorylated by ERK and this
Adaptive Response to Kinase Inhibition

Modification is thought to stabilize the protein, which could contribute to regulating Ras and control of BrAf and Raf1 activation. This complex feedback regulation of upstream members of the ERK signaling network was recently reviewed in detail (25). Of clinical significance, the mutation of BrAfV600E to E/K activates its kinase activity and makes it insensitive to ERK-mediated inhibition of upstream signaling components, effectively circumventing the feedback control of this upstream activation network.

There are currently two BrAf inhibitors approved for treatment of malignant melanoma, vemurafenib and dabrafenib (39–41). Both are ATP-competitive inhibitors and inhibit BrAfV600E/K as well as wild-type BrAf and Raf1. Vemurafenib and dabrafenib have IC50s of 10 and 0.8 nmol/L for purified BrAfV600E, respectively, being 4- to 8-fold less potent toward wild-type Raf proteins. Both vemurafenib and dabrafenib have significant clinical response in patients with BrAfV600E/K melanoma (39, 40, 42). In contrast, patients with wild-type BrAf do not respond to these inhibitors because of a paradoxical Raf activation leading to significant ERK activity (43–45). MEK inhibitors, such as trametinib, inhibit ERK activation in melanoma and have shown positive clinical responses with BrAfV600E/K melanoma but at a lower response rate than BrAf inhibitors (45). Clinical studies have shown that concurrent administration of BrAf and MEK inhibitors is significantly more active in patients with BrAf-mutant melanoma than either single agent alone (39). The concurrent administration of dabrafenib and trametinib was associated with a higher incidence of complete response (9% vs. 4%) and longer progression-free survival (9.4 vs. 5.8 months) compared with dabrafenib alone. Even though the combination of BRAF/MEK inhibitors is initially highly effective in treating melanoma, progression to resistance ultimately occurs (45). Several mechanisms have been defined for melanoma progression to BrAf inhibitor resistance that increase the activation of ERK including mutation of NRas (46), loss of NF1 (47, 48), overexpression of BrAf or Raf1 (49, 50), splice variants of BrAf that dimerize independent of Ras (36), increased expression of Tpl2/Cot (51), activating MEK mutations (52, 53), and the induction of specific receptor tyrosine kinases (54, 55). Increased activity of the Akt–mTOR pathway has also been defined as a resistance mechanism in melanoma (56). Lito and colleagues have referred to such resistance mechanisms as “adaptive resistance” (25). The end result of these resistance mechanisms is that the tumor cell is less dependent on the targeted oncprotein.

It is now realized that many tumors respond to targeted inhibitors with rapid adaptive changes in signaling networks that allow bypass of targeted oncprotein inhibition. This is true with targeted kinase inhibitors, such as dabrafenib and trametinib, as described above as well as specific inhibitors for AKT (57), mTOR (58), and many receptor tyrosine kinases such as EGFR and HER2 (39–61). It is this adaptive response to targeted kinase inhibitors that contributes to the failure of single-agent kinase inhibitors to have durable responses. This failure is dramatic in melanoma but is seen in virtually all cancers treated with single-agent kinase inhibitors, most of which are not as dependent on a single signaling pathway such as BrAf–MEK–ERK in melanoma.

Recently, chemical proteomic methods have been developed that allow assay en masse of the activation state of 75% to 80% of the expressed kinome in tumor cells (37). Study of the kinome response in TNBC to MEK inhibition by selumetinib or trametinib demonstrated a rapid upregulation of multiple receptor tyrosine kinases due to loss of ERK activation (37). In both cell lines and genetically engineered mouse models (GEMM) of TNBC, MEK inhibition induced the upregulation of Axl, DDR1/2, KDR, PDGFRβ, and additional receptor tyrosine kinases. The upregulation of the receptors was accompanied by increased expression of the cytokines for these receptors effectively establishing autocrine/paracrine loops that activate the receptor kinase activity. Measurement of kinome activation dynamics demonstrated that the upregulated and activated tyrosine kinases in MEK inhibitor–treated tumor cells stimulated the activity of additional tyrosine kinases including many Src family kinases and serine/threonine kinases represented in each of the kinase subfamilies of the kinome (37). The findings demonstrate a resiliency of the kinome that readily allows bypass of targeted kinase inhibition. We have referred to this dynamic response as “kinome reprogramming” because the response is broad and involves kinases in each of the seven subfamilies of the kinome.

It was also evident in these studies that the induction and activation of receptor tyrosine kinases was driving escape from MEK inhibition (37, 62). The chemical proteomic methods used to analyze kinome reprogramming identify kinases using mass spectrometry, which allows identification of specific phosphorylated tyrosines, serines, and threonines in closely related proteins such as the phospho-sites in the activation loops of MEK1 and MEK2 that are not distinguished by available antibodies. It was found that the activity of both MEK1 and 2 was initially inhibited by selumetinib treatment of TNBC cells and tumors, but with continued administration of selumetinib MEK1 remained inhibited but MEK2 escaped inhibition, allowing reactivation of ERK. Thus, MEK2 selectively escapes inhibition by allosteric MEK inhibitors.

The mechanism for selective MEK2 escape from inhibition has significant clinical implications for the use of MEK inhibitors as single agents. MEK inhibitors, such as trametinib and selumetinib, bind to an allosteric regulatory site conserved in MEK1 and MEK2 (8). Binding of trametinib, selumetinib, and other MEK inhibitors to this allosteric regulatory site inhibits MEK1 and 2 kinase activity toward ERK1/2. In response to MEK inhibition, the adaptive response leads to upregulated receptor tyrosine kinases that stimulate the formation of GTP-bound Ras, leading to Ras-induced dimerization and activation of Raf (Fig. 2). Activated Raf kinases phosphorylate two conserved serines on the activation loops of MEK1 and 2. This dual serine phosphorylation is required for MEK1 and 2 activation, leading to phosphorylation of ERK1/2 (8). As the MEK activation loop serines become phosphorylated by Raf, the...
affinity of MEK inhibitors decreases significantly for the allosteric regulatory site that they bind. When both activation loop serines are phosphorylated, the affinity of MEK inhibitors for binding to the allosteric regulatory site is decreased by 20-fold (63, 64), effectively diminishing the potency of the inhibitors (Fig. 2). In addition, MEK1 encodes a threonine at position 292 (MEK1T292) that is absent in MEK2 (8, 65). MEK1 T292 is phosphorylated by ERK and functions as a negative feedback regulatory site functionally inhibiting MEK1 (65). This site is not conserved in MEK2, so that when MEK1 and 2 are phosphorylated on their activation loops and regain activity due to diminished potency of the allosteric inhibitor, ERK can be at least partially reactivated. MEK1 would be subject to feedback inhibition but the activated MEK2 would escape.

Concluding Remarks

The observation that MEK2 can escape from inhibition by allosteric site inhibitors suggests that MEK inhibitors will need to be used in combination with other inhibitors. But in tumors where BRaf is wild-type, paradoxical Raf activation will result from treatment with Raf inhibitors and would result in an even greater adaptive response. ERK inhibitors are currently in preclinical development and have been shown in cell lines to inhibit the emergence of MEK inhibitor resistance as well as overcome acquired resistance to MEK inhibitor (66, 67). Thus, cotargeting MEK and ERK may provide significantly more durable responses than either agent alone. It must be noted that both MEK and ERK inhibitors will cause loss of ERK activity and initiate adaptive responses involving upregulation of receptor tyrosine kinases that will not only activate the Ras–Raf network but alternative pathways such as PI3K–AKT. This has led to the proposed use of intermittent BRaf inhibitor treatments (68) or combination therapies that includes an inhibitor of the Raf–MEK–ERK pathway and receptor tyrosine kinase inhibitor (54, 55). An example of the latter is lapatinib in combination with vemurafemib in thyroid carcinoma having BRafV600E mutation (69).

Given the heterogeneity of adaptive responses to targeted kinase inhibitors and the resiliency of the kinome to effectively bypass targeted inhibition, it seems that combinations of specific kinase inhibitors can prolong clinical response but resistance and disease progression will ultimately occur. For targeted kinase inhibitors to have truly durable responses, novel therapeutic strategies will need to be developed. We propose that it is necessary to prevent the upregulation of receptor tyrosine kinases and the adaptive
kinome reprogramming that is seen with targeted kinase inhibition. A more complete understanding of the molecular mechanisms of adaptive kinome reprogramming will be required to effectively develop therapeutic approaches to arrest and prevent the progression to resistance seen with kinase inhibitors.

Disclosure of Potential Conflicts of Interest

G.L. Johnson is an employee of KinoDyn, Inc. and has ownership interest (including patents) in KinoDyn, Inc. L.M. Graves has ownership interest (including patents) in KinoDyn, Inc. No potential conflicts of interest were disclosed by the other authors.

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