Anticancer therapy: boosting the bang of Bim

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Even though activating mutations of B-Raf, a kinase atop the MAPK signaling cascade, reportedly sensitize tumor cells to MEK inhibitors, Raf and MEK inhibitors have exhibited limited clinical activity. In this issue of the JCI, Cragg et al. report that MEK inhibition upregulates the proapoptotic Bcl-2 family member Bim but induces little regression of human melanoma xenografts in mice unless the Bcl-2 antagonist ABT-737 is added (see the related article, doi:10.1172/JCI35437). These findings illustrate the potential benefit of simultaneously inhibiting oncogenic kinases and inhibiting Bcl-2 action in solid tumors.

Effects of MAPK pathway activation on Bcl-2 family members

In addition to enhancing cell proliferation, the MAPK pathway also regulates the mitochondrial pathway of apoptosis, a pathway in which the oncoprotein Bcl-2 and related proteins play a prominent role (8–10). Based on structural and functional criteria, members of this protein family can be subdivided into 3 classes. The first class, which contains Bcl-2, Bcl-xL, Mcl-1, Bcl-w, and A1, inhibits apoptosis by binding to proapoptotic Bcl-2 family members. The second class includes Bax and Bak, which are involved in releasing proapoptotic proteins from mitochondria, possibly by forming pores in the outer mitochondrial membrane. The third class, called Bcl-2 homology 3-only (BH3-only) proteins, includes Bim, Bad, Noxa, Bmf, and several other family members, all of which contain a 9–15-amino acid BH3 domain that is thought to be important in binding and neutralizing antiapoptotic Bcl-2 family members.

The BH3-only proteins appear to serve as molecular stress sensors within cells (9). Two of the family members, Noxa and Puma, are transcriptionally upregulated in response to DNA damage and other stimuli. Other family members such as Bim are constitutively expressed but sequestered by binding to polypeptides in various cellular compartments. In response to various stresses (e.g., cytoskeletal disruption or loss of growth signals), specific BH3-only proteins are released and activated. At least 2 models have been proposed to explain the subsequent induction of apoptosis (8–10). One model focuses on the purported ability of some of these polypeptides to directly activate Bax and Bak, thereby causing release of cytochrome c from mitochondria (10). The other focuses exclusively on the ability of all of these family members to bind and inactivate antiapoptotic Bcl-2 molecules (8).

The activities of Bcl-2 family members are regulated, in part, by posttranslational modifications. Antiapoptotic kinases, for example, catalyze activating phosphorylations of Bcl-2 (11, 12) and Mcl-1 (13, 14) as well as inactivating phosphorylations of Bad and Bim (15, 16). While some of these phosphorylations are mediated through

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Commentaries

Oncogenic activation of the Raf/MEK/ERK pathway

Over the past decade, an increasingly detailed understanding of the molecular pathogenesis of cancer has led to identification of a variety of new targets for anticancer drugs. Two of the best-studied signaling pathways that are activated by oncogenic kinase mutations are the MAPK pathway and the PI3K/Akt pathway (Figure 1). According to current understanding, the former pathway involves signaling from a variety of receptor tyrosine kinases through adaptor molecules that activate the small GTPase Ras. Upon activation, Ras binds and activates members of the Raf serine/threonine protein kinase family, thereby triggering sequential phosphorylation and activation of the MEK kinases and their downstream targets ERK1 and ERK2. Upon activation, ERK1 and ERK2 phosphorylate a number of cytoplasmic and nuclear substrates involved in cell survival and proliferation. In the nucleus, ERK-mediated phosphorylation of c-myc, ELK1, and other transcription factors leads to increased expression of genes involved in cell cycle progression (1). In the cytoplasm, ERK-induced phosphorylation of Bcl-2 family members has been reported to inhibit apoptosis, as described below.

In addition to the MAPK pathway, receptor tyrosine kinases and Ras activate PI3K, which generates the lipid second messenger phosphatidylinositol-3,4,5-trisphosphate (PIP3), again setting into motion a protein kinase signaling cascade. PIP3 activates the serine/threonine kinase phosphoinositide-dependent kinase 1, which catalyzes the activating phosphorylation of Akt. Akt in turn phosphorylates a number of proteins (e.g., the cyclin-dependent kinase inhibitor p27(Kip1)) that regulate cell cycle progression as well as transcription factors (e.g., NF-κB, Foxo3a) and other molecules that limit susceptibility of cells to apoptosis.

Studies performed over the past decade have revealed many ways in which one or both of these pathways are activated in tumor cells. Signaling is initiated not only by mutations that lock Ras in its GTP-bound (i.e., activated) state, but also by mutations of receptor tyrosine kinases such as EGFR and the EGFR family member HER2/Neu. Particularly pertinent to the present discussion are the more recently described activating mutations of Ras, which occur in almost 70% of melanomas, 30% of thyroid cancers, 15% of ovarian cancers, and 10% of colorectal cancers (2, 3). Whereas activating mutations of EGFR confer hypersensitivity to EGFR tyrosine kinase inhibitors such as gefitinib (4), B-RAF mutations have been reported to uniquely confer sensitivity to MEK inhibitors (5). Despite these observations, clinical studies of MEK and Raf inhibitors have yielded relatively disappointing results, even in patients with mutations that activate the MAPK pathway (3, 6, 7). While it is clearly possible for MEK inhibitors to inhibit growth of xenografts with activating B-RAF mutations (5), tumor regressions have been the exception rather than the rule in preclinical models and in the clinical setting, raising concern that some other pathway also needs to be modulated in order to facilitate tumor shrinkage.
the Akt pathway, others clearly involve ERK1/2 or their immediate downstream target p90 ribosomal S6 kinase.

Enhancing the effects of upregulated Bim
Building on previous reports showing that ERK-mediated Bim phosphorylation leads to proteasome-mediated Bim degradation (15, 16), Cragg et al. report in the current issue of the *JCI* that MEK inhibition leads to Bim upregulation in a variety of B-RAF mutant human melanoma and colon cancer cell lines (17). Interestingly, however, the MEK inhibitors induce modest apoptosis in vitro and exhibit little antitumor effect on melanoma xenografts in mice in vivo. Results of further experiments suggest that the upregulated Bim is bound and presumably neutralized by Bcl-2 and Bcl-xL (Figure 1). Consistent with this interpretation, Cragg et al. show that the BH3 mimetic ABT-737, which binds to and inhibits Bcl-2 and Bcl-xL, increases MEK inhibitor–induced apoptosis in vitro and slows tumor growth — sometimes dramatically — in vivo.

Questions and future perspectives
The present study by Cragg et al. (17) represents an elegant step forward in translating
current understanding of apoptotic pathways into potentially improved therapies. Nonetheless, important questions remain. The mechanistic basis for the apparent synergy of MEK inhibitors and a BH3 mimic remains incompletely understood. While the results reported by Cragg et al. show that Bim shRNA protects cells from MEK inhibitor-induced death at early time points (17), Bim shRNA is much less protective with extended treatment. These observations raise the possibility that a second cytotoxic mechanism might be triggered during prolonged MEK inhibition. Earlier observations that the Raf/MEK/ERK pathway regulates stability of the antiapoptotic protein Mcl-1 (14, 18), as well as antiapoptotic activity of Bcl-2 itself (11, 12), raise the possibility that Mcl-1 downregulation and/or Bcl-2 dephosphorylation might also contribute to the cytotoxic effects of MEK inhibition. A possible contribution from interruption of ERK-mediated phosphorylation of other Bcl-2 family members also remains to be investigated. Finally, the effects of these agents on normal cells require further study. Although it is convenient to invoke the idea that selectivity comes from the phenotype of oncogene addiction (19), i.e., the dependence of a cancer cell on one overactive gene or pathway for its survival and growth, the apoptosis resulting from drug-induced Bim upregulation combined with Bcl-2 inhibition described by Cragg et al. might be predicted to cause substantial toxicity in normal cells as well.

Compared with certain other attempts to alter Bcl-2 family members for therapeutic benefit (20), the effects of combined MEK inhibitor/BH3 mimetic therapy appear particularly promising. However, the ability to translate these findings into the clinic will depend on the toxicities encountered. The dose-limiting toxicities of MEK inhibition appear to be rash and hypoxia (1), but the dose-limiting toxicities of BH3 mimetics in humans have not yet been reported. Although the toxicities of this therapeutic combination in mice were reportedly tolerable in the current study (17), it remains to be seen whether these classes of agents can be combined at therapeutic doses and without toxic side effects in the clinic.

In view of the potential benefit of simultaneously inhibiting the MAPK pathway and antagonizing Bcl-2 in tumors with B-RAF mutations, it is reasonable to ask whether this approach will also work in tumors driven by other oncogenic kinases. Additional studies from the same research group indicate that the BCR/ABL kinase inhibitor imatinib and the EGFR tyrosine kinase inhibitor gefitinib also induce apoptosis, at least in part, through Bim upregulation (ref. 17 and references therein). Because BCR/ABL and EGFR activate signaling through the Akt pathway as well as the MAPK pathway (Figure 1), it is slightly surprising that Bim upregulation is the only prominent change in Bcl-2 family members observed with MEK, BCR/ABL, and EGFR inhibitors. In all cases, however, ABT-737 enhances the effect of the kinase inhibitor. Accordingly, one wonders whether the MEK inhibitor/BH3 mimetic therapy would also be active in other tumors that exhibit MAPK activation in the absence of B-RAF mutations.

Finally, while there is some evidence that MEK might represent a better target than Raf (3), the Raf inhibitor sorafenib is in fact approved for certain therapeutic indications, raising the question of what would happen if tumors harboring B-RAF mutations were treated with ABT-737 plus sorafenib rather than experimental MEK inhibitors. Answers to all of these questions are awaited with interest.

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