preventative effect of premedication on oxaliplatin-related hypersensitivity are scant.

In our study, all patients received mFOLFOX6. Kim et al. retrospectively investigated 247 patients given oxaliplatin-containing regimens and reported that the incidences of hypersensitivity reactions did not depend on the oxaliplatin-containing regimen employed [6]. The modified premedication regimen used in the present study might thus be useful for the management of hypersensitivity reactions to other oxaliplatin-containing regimens.

The patient characteristics were well balanced between the cohorts. The median number of cycles increased from 9 to 12 when modified premedication was used instead of routine premedication. This three-cycle increase in the median number of cycles administered to patients who received modified premedication is particularly important, because prolonged therapy might contribute to improved survival. In cohort 2, patients could receive mFOLFOX6 plus bevacizumab, newly approved in Japan. The addition of bevacizumab to oxaliplatin-based, first-line chemotherapy has been shown to significantly improve progression-free survival in patients with metastatic colorectal cancer [14, 15]. We therefore examined if increasing the number of treatment cycles was associated with the inclusion of bevacizumab. The median number of cycles in patients who additionally received bevacizumab was similar to that in patients treated with mFOLFOX6 without bevacizumab. We found no association between bevacizumab and the number of cycles administered to cohort 2. Bevacizumab thus apparently did not contribute to a longer duration of treatment. Kim et al. [6] reported that anti-vascular epithelial growth factor (anti-VEGF) monoclonal antibody bevacizumab was not associated with hypersensitivity reactions when given with combination chemotherapy regimens. Consistent with their results, we found no difference in the frequency of hypersensitivity reactions according to the presence or absence of bevacizumab.

The major reasons for discontinuing treatment with mFOLFOX6 were neurotoxicity and hypersensitivity reactions. Neurotoxicity was the most remarkable as well as the most common dose-limiting factor. Treatment withdrawal was based on the highest grade adverse effects occurring during the previous cycle. Sensory neuropathy was treatment limiting in patients who received FOLFOX4 (85 mg/m$^2$ oxaliplatin) because it generally occurred after 8–10 cycles [16]. Tournigand et al. [17] reported that oxaliplatin was associated with grade 3 neuropathy in 20% of patients who received FOLFOX6 (100 mg/m$^2$ oxaliplatin) and in 34% of patients after 12 cycles. In our study, neurotoxicity was the reason for discontinuing treatment in 20% of the patients in cohort 1, as compared with 53% of those in cohort 2. These reports supported our results that a decreased frequency of hypersensitivity reactions was associated with an increased rate of treatment discontinuation caused by neurotoxicity.

If treatment is discontinued because of neurotoxicity, oxaliplatin-based therapy may be able to be resumed after this adverse effect resolves. This strategy enables treatment for longer periods. When oxaliplatin is used in an adjuvant setting, in which the median number of courses of treatment ranges from 10 to 12, it is important to note that the use of modified premedication reduced the frequency of hypersensitivity reactions from 20% to 7.0%, allowing treatment to be completed as planned. Completion of adjuvant treatment by our strategy may reduce the relapse rate, thereby contributing to improved survival.

The exact mechanism responsible for platinum-related hypersensitivity reactions is unknown, but several mechanisms may be involved. Hypersensitivity reactions have been linked to the release of histamine and other vasoactive substances and ascribed to type I hypersensitivity IgE-mediated reactions [9, 18]. Hypersensitivity reactions usually develop after multiple infusions of oxaliplatin (7 on average) [19], clearly showing that repeated exposure to the drug is prerequisite to the induction of an allergic immune response.

The optimal strategy for resuming treatment after discontinuation caused by an episode of hypersensitivity remains controversial. Because resumption of treatment can be fatal, several preventive procedures have been proposed. Patient desensitization is of interest because of its consistent efficacy but has been studied in only a small number of subjects [19]. Moreover, desensitization is cumbersome to implement. The prick test, using a concentration of 1 mg/ml oxaliplatin, appears not to be very sensitive. Skin tests are useful for detecting IgE-mediated reactions, but their sensitivity is not high enough. When hypersensitivity reactions to oxaliplatin do occur, symptoms generally subside on discontinuation of treatment and administration of steroids and antihistamines. Mild sensitivity reactions to oxaliplatin can be controlled by treatment with antihistamines, steroids, or both. Interestingly, all the patients in cohort 1 of our study received premedication with dexamethasone 8 mg and granisetron 3 mg as a part of a "standard antiemetic" regimen before the infusion of oxaliplatin. In cohort 2, we confirmed that modified premedication with an increased dose of dexamethasone plus an antihistamine effectively decreased hypersensitivity reactions. Premedication was not associated with any side effects. In particular, adverse events potentially associated with a high dose of dexamethasone, such as exacerbation of diabetes, osteoporosis, and compression fractures, did not occur.

In conclusion, our study showed that modified premedication with an increased dose of dexamethasone plus an antihistamine from the sixth cycle of mFOLFOX6

greatly reduced the frequency of hypersensitivity reactions, an important dose-limiting toxic effect of oxaliplatin. A reduced incidence of hypersensitivity reactions to oxaliplatin enhances the effectiveness of mFOLFOX6 by allowing treatment to be prolonged. Our results were statistically significant, although the study was performed in a single institution. We therefore recommend our modified premedication regimen to reduce hypersensitivity reactions in clinical practice. Phase III prospective studies are highly warranted to confirm the effectiveness of modified premedication.

**Conflict of interest** No author has any conflict of interest.

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Clinical Cancer Research

*Human Cancer Biology*

# Role of ERK-BIM and STAT3-Survivin Signaling Pathways in ALK Inhibitor–Induced Apoptosis in EML4-ALK–Positive Lung Cancer

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## Abstract

**Purpose:** *EML4-ALK* (echinoderm microtubule-associated protein–like 4 anaplastic lymphoma kinase) was recently identified as a transforming fusion gene in non–small cell lung cancer. The purpose of the present study was to characterize the mechanism of malignant transformation by EML4-ALK.

**Experimental Design:** We established NIH 3T3 cells that stably express variant 1 or 3 of EML4-ALK and examined the signaling molecules that function downstream of EML4-ALK.

**Results:** Forced expression of EML4-ALK induced marked activation of extracellular signal–regulated kinase (ERK) and STAT3, but not that of AKT. Inhibition of ERK or STAT3 signaling resulted in substantial attenuation of the proliferation of cells expressing either variant of EML4-ALK, suggesting that these signaling pathways function downstream of EML4-ALK in lung cancer cells. The specific ALK inhibitor TAE684 induced apoptosis that was accompanied both by upregulation of BIM, a proapoptotic member of the Bcl-2 family, and by downregulation of survivin, a member of the inhibitor of apoptosis protein (IAP) family, in EML4-ALK–expressing NIH 3T3 cells as well as in H3122 human lung cancer cells harboring endogenous EML4-ALK. Depletion of BIM and overexpression of survivin each inhibited TAE684-induced apoptosis, suggesting that both upregulation of BIM and downregulation of survivin contribute to TAE684-induced apoptosis in EML4-ALK–positive lung cancer cells. Furthermore, BIM and survivin expression was found to be independently regulated by ERK and STAT3 signaling pathways, respectively.

**Conclusions:** ALK inhibitor–induced apoptosis is mediated both by BIM upregulation resulting from inhibition of ERK signaling as well as by survivin downregulation resulting from inhibition of STAT3 signaling in EML4-ALK–positive lung cancer cells. *Clin Cancer Res; 17(8); 1–9. ©2011 AACR.*

## Introduction

Lung cancer is the leading cause of cancer deaths worldwide. Given that the efficacy of conventional chemotherapeutic agents with regard to improving clinical outcome in lung cancer patients is limited, target-based therapies are being pursued as potential treatment alternatives. Somatic mutations in the tyrosine kinase domain of the epidermal growth factor receptor (EGFR) have been associated with tumor responsiveness to EGFR tyrosine kinase inhibitors (TKI) in a subset of individuals with non–small cell lung cancer (NSCLC; refs. 1–3). Such findings suggest that the use of molecularly targeted therapy in genetically defined subsets of cancer patients may prove to be an effective strategy for the treatment of many cancers including NSCLC. Given that lung cancer is a common type of cancer, the identification of even small subsets of lung cancer patients harboring specific genetic abnormalities will translate into the provision of large cohorts for targeted therapy.

A recent study identified a potential driver mutation in NSCLC: fusion of the echinoderm microtubule-associated protein–like 4 gene (*EML4*) with the anaplastic lymphoma kinase gene (*ALK*), which results in the production of a fusion protein (EML4-ALK) consisting of the $NH_2$-terminal portion of EML4 and the COOH-terminal region of ALK (4). ALK was originally discovered as the result of characterization of chromosomal translocations that lead to the expression of fusion proteins consisting of the COOH-terminal kinase domain of ALK and the $NH_2$-terminal portion of nucleophosmin (NPM) in patients with anaplastic large cell lymphoma (5, 6). Various break and fusion points within the *EML4* locus in NSCLC cells give rise to different isoforms of EML4-ALK, which appear to be present in 5% to 10% of NSCLC cases (4, 7–14). The most common EML4-ALK variants are 1 and 3, which together account for about 60% of EML4-ALK–positive lung cancer cases (14). All EML4-ALK isoforms undergo constitutive oligomerization mediated by the coiled coil domain of the

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**Note:** Supplementary data for this article are available at Clinical Cancer Research Online (http://clincancerres.aacrjournals.org/).

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doi: 10.1158/1078-0432.CCR-10-2798

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**Translational Relevance**

*EML4-ALK* (echinoderm microtubule-associated protein–like 4 anaplastic lymphoma kinase) was recently identified as a transforming fusion gene in non–small cell lung cancer (NSCLC), and several selective inhibitors of the kinase activity of ALK, such as crizotinib, are currently undergoing clinical trials for the treatment of EML4-ALK–positive NSCLC. Identification of the signaling pathways responsible for malignant transformation by EML4-ALK will likely enhance further development of ALK-targeted therapy for NSCLC patients. We have now shown that both ERK (extracellular signal–regulated kinase) and STAT3 pathways are the principal mediators of EML4-ALK signaling, and we further identified the mediators of apoptosis induced by ALK inhibition. Our preclinical data provide both insight into the pathogenesis of EML4-ALK–positive lung cancer and a potential basis for the development of biomarkers for the efficacy of ALK-targeted therapy in patients with this condition.

EML4 portion, which confers marked transforming activity both *in vitro* and *in vivo* (4, 15).

ALK inhibitors have been found to suppress the growth of and to induce apoptosis in EML4-ALK–positive lung cancer cells, suggesting that ALK inhibition is a potential strategy for the treatment of NSCLC patients with this molecular abnormality (9, 16). Indeed, a selective inhibitor of the kinase activity of ALK, crizotinib, is currently undergoing clinical trials and has shown high efficacy in NSCLC patients with EML4-ALK (17). However, the downstream signaling pathways that regulate the proliferation or survival of EML4-ALK–positive lung cancer cells have remained to be well established, and the key mediators of ALK inhibitor–induced apoptosis have not been fully determined. In the present study, we constructed expression vectors for EML4-ALK variants 1 and 3 and then established cells stably expressing these proteins. With the use of these cells, we examined the signaling molecules that function downstream of EML4-ALK. We further investigated the molecular mechanisms underlying ALK inhibitor–induced apoptosis in EML4-ALK–positive lung cancer cells.

## Materials and Methods

### Cell culture and reagents

NIH 3T3 cells as well as the human cancer cell lines H2228 and Karpas299 were obtained from American Type Culture Collection. H3122 cells were obtained as previously described (9). NIH 3T3 cells were cultured in Dulbecco's modified Eagle's medium (Sigma) supplemented with 10% FBS and 1% penicillin-streptomycin. H2228, Karpas299, and H3122 cells were cultured in RPMI 1640 medium (Sigma) supplemented with 10% FBS and 1% penicillin-streptomycin. All cells were maintained under a humidified atmosphere of 5% $CO_2$ at 37°C. U0126 and LY294002 were obtained from Cell Signaling Technology and TAE684 was from ShangHai Biochempartner.

### Cell transfection

A cDNA for EML4-ALK variant 1 was cloned into pDNR-Dual (Becton Dickinson) as previously described (9). A full-length cDNA fragment encoding EML4-ALK variant 3b was obtained from H2228 cells by reverse transcription and the PCR with the primers EAV-F (5′-AAGCTTCGCAAGATGGACGGTTTCGCCGGCAGTC-3′) and EAV-R (5′-GCGGCCGCTCAGGGCCCAGGC-TGGTTCATGCT-3′). Amplification products were verified by sequencing after their cloning into the pCR-Blunt II-TOPO vector (Invitrogen). The EML4-ALK variant 1 or 3b cDNA was excised from pCR-Blunt II-TOPO and transferred to either pcDNA3.1-Hygro(+) (Invitrogen) or pMZs (Cell Biolabs). A pBabe-puro vector encoding CA-STAT3 with a COOH-terminal FLAG tag was kindly provided by I. Bromberg (18). A pQCXIH-survivin vector was constructed as previously described (19). All expression vectors were introduced into NIH 3T3 cells as previously described (20, 21).

### Immunoblot analysis

Cells were washed twice with ice-cold PBS and then lysed in a solution containing 20 mmol/L Tris-HCl (pH 7.5), 150 mmol/L NaCl, 1 mmol/L EDTA, 1% Triton X-100, 2.5 mmol/L sodium pyrophosphate, 1 mmol/L phenylmethylsulfonyl fluoride, and leupeptin (1 μg/mL). The protein concentration of cell lysates was determined with the Bradford reagent (Bio-Rad), and equal amounts of protein were subjected to SDS-PAGE on a 7.5% or 12% gel. The separated proteins were transferred to a nitrocellulose membrane, which was then exposed to 5% nonfat dried milk in PBS for 1 hour at room temperature before incubation overnight at 4°C with primary antibodies. Rabbit polyclonal antibodies to human phosphorylated ALK (pY1608), to ALK, to phosphorylated extracellular signal–regulated kinase (ERK), to ERK, to phosphorylated STAT3, to STAT3, to phosphorylated AKT, to AKT, to PARP, to BIM, to Mcl-1, to Bcl-xL, to X-linked inhibitor of apoptosis (XIAP), and to FLAG were obtained from Cell Signaling Technology; those to survivin were from Novos; and those to β-actin were from Sigma. All antibodies were used at a 1:1,000 dilution, with the exception of those to β-actin (1:200). The membrane was then washed with PBS containing 0.05% Tween 20 before incubation for 1 hour at room temperature with horseradish peroxidase–conjugated goat antibodies to rabbit IgG (Sigma). Immune complexes were finally detected with chemiluminescence reagents (GE Healthcare).

### Cell growth inhibition assay

Cells were plated in 96-well, flat-bottomed plates and cultured for 24 hours before exposure to various concentrations of drugs for 72 hours. TetraColor One (5 mmol/L tetrazolium monosodium salt and 0.2 mmol/L 1-methoxy-5-methyl phenazinium methylsulfate; Seikagaku) was then

added to each well, and the cells were incubated for 3 hours at 37°C before measurement of absorbance at 490 nm with a Multiskan Spectrum instrument (Thermo Labsystems).

### RNA interference

Cells were plated at 50% to 60% confluence in 6-well plates or 25-cm$^2$ flasks and then incubated for 24 hours before transient transfection for the indicated times with siRNAs mixed with the Lipofectamine reagent (Invitrogen). The siRNAs specific for STAT3 mRNA (STAT3-1, 5′-UCAUUGACCUUGUGAAAAA-3′; STAT3-2, 5′-GCAAAAA-GUUUCCUACAAA-3′), ALK mRNA (ALK-1, 5′-ACACC-CAAAUUAAUACCAA-3′; ALK-2, 5′-UCAGCAAAUUCAA-CCACCA-3′), ERK mRNA (ERK-1, 5′-CAAGAGGAUUGAA-GUAGAA-3′; ERK-2, 5′-UCAGCCCCUUUGAGCACCA-3′), or BIM mRNA (BIM-1, 5′-GGAGGGUAUUUUUGAAUAA-3′; BIM-2, 5′-AGGAGGGUAUUUUUGAAUA-3′) as well as a nonspecific siRNA (5′-GUUGAGAGAUAUUAGAGUU-3′) were obtained from Nippon EGT. The cells were then subjected to immunoblot analysis or the annexin V–binding assay. All data presented were obtained with STAT3-1, ALK-1, ERK-1, or BIM-1 siRNAs, but similar results were obtained with STAT3-2, ALK-2, ERK-2, and BIM-2 siRNAs.

### Annexin V–binding assay

Binding of annexin V to cells was measured with the use of an Annexin-V-FLUOS Staining kit (Roche). Cells were harvested by exposure to trypsin-EDTA, washed with PBS, and centrifuged at 200 × *g* for 5 minutes. The cell pellets were resuspended in 100 μL of Annexin-V-FLUOS labeling solution, incubated for 10 to 15 minutes at 15°C to 25°C, and then analyzed for fluorescence with a flow cytometer (FACSCalibur) and Cell Quest software (Becton Dickinson).

### Statistical analysis

Quantitative data are presented as means ± SD and were analyzed by Student's 2-tailed *t* test. A value of $P < 0.05$ was considered statistically significant.

## Results

### Oncogenic EML4-ALK tyrosine kinase activates ERK and STAT3 signaling pathways

To study the function of oncogenic EML4-ALK, we established nontransformed mouse fibroblast (NIH 3T3) cells that either stably express EML4-ALK variant 1 or 3 (3T3/EAV1 and 3T3/EAV3 cells, respectively) or stably harbor the corresponding empty vector (3T3-Mock cells). Immunoblot analysis revealed that EML4-ALK variant 1 or 3 was detected with antibodies to ALK at positions corresponding to molecular sizes of about 120 and 90 kDa, respectively, in the transfected cells (Fig. 1A). The kinase activity of the EML4-ALK variants was activated as revealed by immunoblot

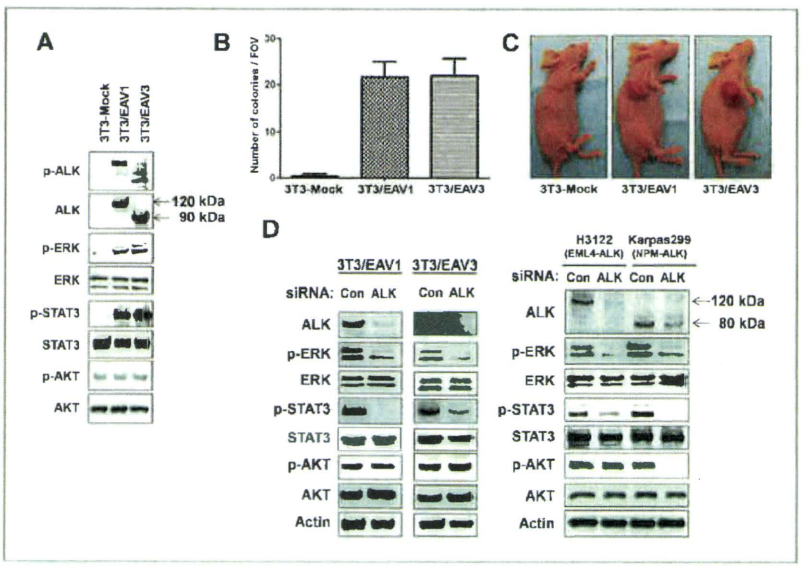


Figure 1. Effects of stable forced expression of EML4-ALK variant 1 or 3 on signaling pathways. A, the indicated stably transfected NIH 3T3 cell lines were lysed and subjected to immunoblot analysis with antibodies to the indicated proteins. B, the indicated cell lines were plated in semisolid medium supplemented with 10% FBS and incubated for 3 to 4 weeks, after which the cells were stained with 0.005% crystal violet and the number of colonies per field of view (FOV) was counted. Data are means ± SD from 3 independent experiments. C, cells ($5 \times 10^6$) of the indicated lines were injected subcutaneously into the axilla of 5-week-old female athymic nude mice. At 18 days after the injection, the large tumors that formed at the injection site for 3T3/EAV1 or 3T3/EAV3 cells were photographed. Data are representative of results obtained with 5 mice per cell line. D, the indicated cell lines were transfected with nonspecific (Con) or ALK siRNAs for 48 hours, after which cell lysates were subjected to immunoblot analysis with antibodies to the indicated proteins.

analysis with antibodies specific for the $Tyr^{1608}$-phosphorylated form of ALK. Consistent with previous observations (4, 15), the 3T3/EAV cells exhibited transforming activity both *in vitro* (Fig. 1B) and *in vivo* (Fig. 1C). We also found that phosphorylation of both the mitogen-activated protein kinase (MAPK) ERK and STAT3 was markedly increased in the cells expressing either variant of EML4-ALK compared with that in 3T3-Mock cells, whereas the phosphorylation level of the kinase AKT was not affected by expression of EML4-ALK (Fig. 1A). To exclude the possibility that these results were due to nonspecific effects of transfection, we depleted both 3T3/EAV1 and 3T3/EAV3 cells of EML4-ALK by RNA interference (RNAi) with ALK siRNA. The phosphorylation of both ERK and STAT3, but not that of AKT, was markedly suppressed by depletion of EML4-ALK (Fig. 1D). Moreover, similar depletion of endogenous EML4-ALK variant 1 in the lung cancer cell line H3122 resulted in marked inhibition of the phosphorylation of ERK and STAT3 without an effect on that of AKT (Fig. 1D). In contrast, the phosphorylation of ERK, STAT3, and AKT was inhibited by ALK siRNA in the NPM-ALK–positive lymphoma cell line Karpas299 (Fig. 1D), in which activation of the phosphoinositide 3-kinase (PI3K)-AKT signaling pathway has been shown to contribute to malignant transformation (22–25). Together, these data suggested that either variant 1 or 3 of EML4-ALK activates ERK and STAT3 signaling pathways but not the PI3K-AKT signaling pathway.

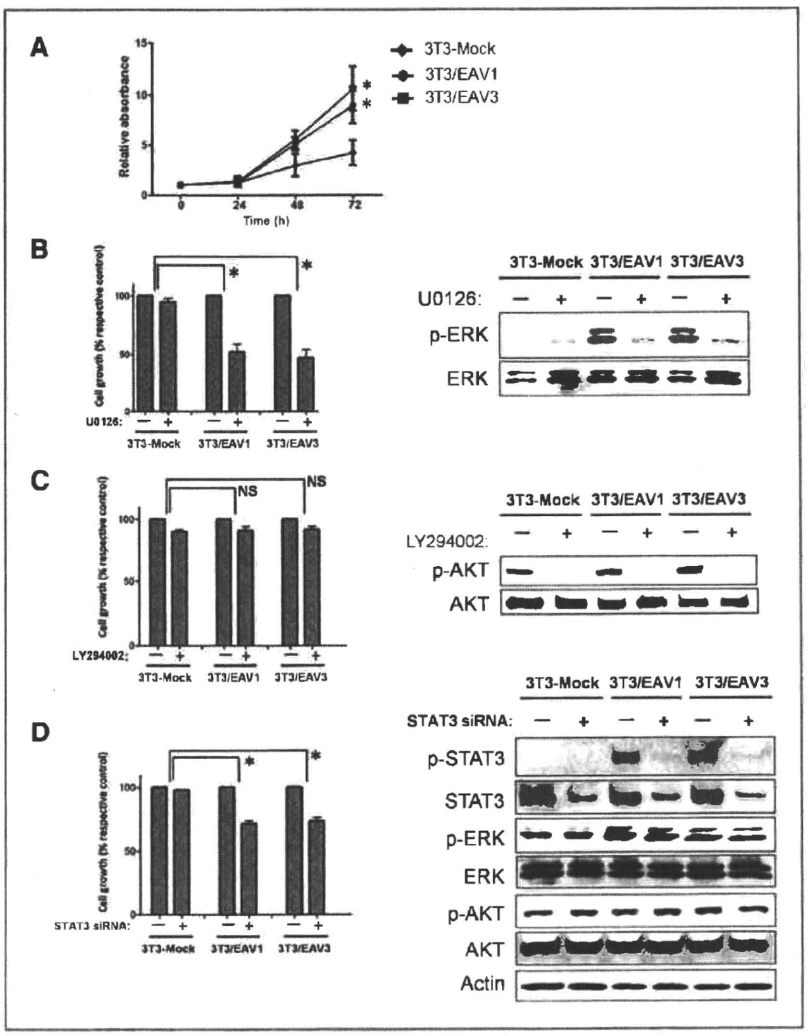


Figure 2. Effects of inhibition of ERK, PI3K, or STAT3 signaling on the growth of cells expressing EML4-ALK. A, the indicated cell lines were incubated in complete medium for the indicated times, after which cell viability was assessed as described in the "Materials and Methods" section. Data are expressed relative to the absorbance value for 3T3-Mock cells at time 0. B and C, cells were incubated in complete medium with or without 10 μmol/L U0126 (B) or 10 μmol/L LY294002 (C) for 72 or 24 hours, after which cell viability was assessed (left) or cell lysates were subjected to immunoblot analysis with antibodies to the indicated proteins (right), respectively. D, cells were transfected with nonspecific or STAT3 siRNAs for 72 or 48 hours, after which cell viability was assessed (left) or cell lysates were subjected to immunoblot analysis with antibodies to the indicated proteins (right), respectively. The abundance of β-actin was examined as a loading control. All quantitative data are means ± SD from 3 independent experiments. *, $P < 0.05$ versus the corresponding value for 3T3-Mock cells or for the indicated comparisons. NS, not significant.

**EML4-ALK promotes cell proliferation through ERK and STAT3 signaling pathways**

We next examined the effect of EML4-ALK on cell proliferation. Both 3T3/EAV1 and 3T3/EAV3 cells proliferated significantly faster than did 3T3-Mock cells (Fig. 2A). To determine the role of intracellular signaling pathways in this action of EML4-ALK, we first examined the effects of chemical inhibitors. We found that U0126, an inhibitor of the ERK kinase MEK, had little effect on the growth of 3T3-Mock cells but that it significantly inhibited the proliferation of both 3T3/EAV1 and 3T3/EAV3 cells at a concentration (10 μmol/L) that resulted in marked inhibition of ERK phosphorylation (Fig. 2B). These data thus suggested that the MEK-ERK signaling pathway contributes to the regulation of cell proliferation by EML4-ALK. We also found that the specific PI3K inhibitor LY294002 had no significant effect on the growth of 3T3-Mock cells or on that of 3T3/EAV1 and 3T3/EAV3 cells at a concentration (10 μmol/L) at which the phosphorylation of AKT was largely abolished (Fig. 2C). To examine the effect of STAT3 inhibition on cell proliferation in cells expressing EML4-ALK, we transfected the cells with an siRNA specific for STAT3 mRNA. Transfection of 3T3-Mock, 3T3/EAV1, or 3T3/EAV3 cells with STAT3 siRNA resulted in marked depletion of STAT3 (Fig. 2D). Whereas such depletion of STAT3 did not affect the proliferation of 3T3-Mock cells, it significantly inhibited that of 3T3/EAV1 and 3T3/EAV3 cells (Fig. 2D). A

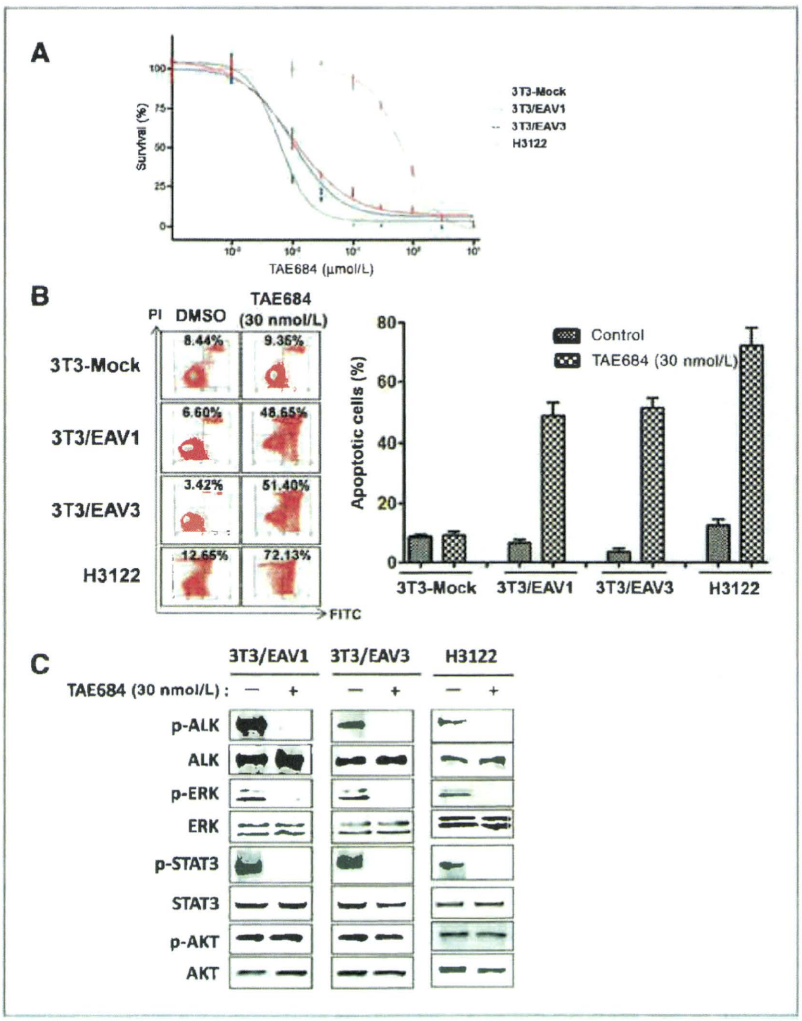


**Figure 3.** Effects of TAE684 on cell growth, apoptosis, and intracellular signaling in cells expressing EML4-ALK. A, the indicated cell lines were cultured for 72 hours in complete medium containing various concentrations of TAE684, after which cell viability was assessed. Data are expressed as percent survival and are means ± SD of triplicates from an experiment that was repeated a total of 3 times with similar results. B, cells were incubated for 48 hours in serum-free medium with 30 nmol/L TAE684 or 0.01% dimethyl sulfoxide (DMSO, vehicle control), after which the proportion of apoptotic cells was determined by staining with fluorescein isothiocyanate (FITC)-conjugated annexin V and propidium iodide (PI) followed by flow cytometry. Representative flow cytometric profiles, with the percentages of FITC-positive, PI-negative (apoptotic) cells indicated, are shown in the left. Quantitative data in the right are means ± SD of triplicates from an experiment that was repeated a total of 3 times with similar results. C, cells were incubated for 24 hours in serum-free medium with or without 30 nmol/L TAE684, after which cell lysates were subjected to immunoblot analysis with antibodies to the indicated proteins.

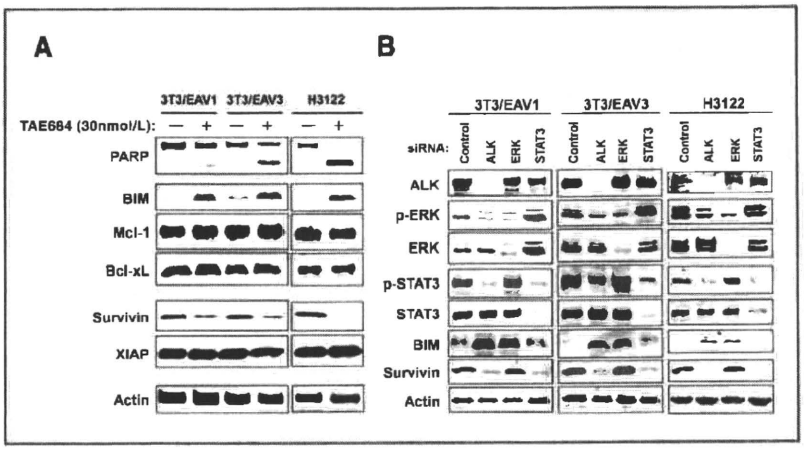


Figure 4. Effects of TAE684 on the expression of apoptosis-related proteins in cells expressing EML4-ALK. A, the indicated cell lines were incubated for 48 hours in serum-free medium with or without 30 nmol/L TAE684, after which cell lysates were subjected to immunoblot analysis with antibodies to the indicated proteins. B, 3T3/EAV1, 3T3/EAV3, or H3122 cells were transfected with nonspecific (control), ALK, ERK, or STAT3 siRNAs for 48 hours, after which cell lysates were subjected to immunoblot analysis with antibodies to the indicated proteins.

second siRNA targeted to a different region of STAT3 mRNA yielded similar results (data not shown). These observations thus suggested that EML4-ALK promotes cell proliferation through both MEK-ERK and STAT3 signaling pathways but not through the PI3K-AKT signaling pathway.

### Effects of ALK inhibition on cell growth and intracellular signaling in EML4-ALK–positive lung cancer cells

To investigate the effects of inhibition of the kinase activity of ALK on cell growth and intracellular signaling in cells expressing EML4-ALK, we used TAE684, a selective and highly potent ALK inhibitor (26). The human lung cancer cell line H3122 expresses endogenous EML4-ALK variant 1 and its growth was found to be highly sensitive to TAE684 (Fig. 3A). Treatment with TAE684 also induced a large increase in the number of apoptotic H3122 cells, as revealed with an annexin V–binding assay (Fig. 3B). Consistent with these results, both 3T3/EAV1 and 3T3/EAV3 cells exhibited a sensitivity to TAE684 that was about 100 times as great as that of 3T3-Mock cells (Fig. 3A), and the level of apoptosis induced by this drug was markedly greater in both 3T3/EAV1 and 3T3/EAV3 cells than in 3T3-Mock cells (Fig. 3B). Immunoblot analysis revealed that TAE684 inhibited the phosphorylation of EML4-ALK in 3T3/EAV1, 3T3/EAV3, and H3122 cells at a concentration (30 nmol/L) at which it substantially inhibited the growth of these cells (Fig. 3C). We further found that TAE684 inhibited the activation of ERK and STAT3, without affecting that of AKT, in all 3 of these cell lines (Fig. 3C). These data thus suggested that the ALK inhibitor induced growth suppression and apoptosis in EML4-ALK–positive lung cancer cells, and that these effects were accompanied by inhibition of ERK and STAT3 signaling pathways but not by that of the PI3K-AKT signaling pathway.

### Effects of ALK inhibition on the expression of apoptosis-related proteins in EML4-ALK–positive lung cancer cells

Given that TAE684 induced apoptosis in cells expressing EML4-ALK, we examined the effects of this drug on the expression of apoptosis-related proteins in such cells. TAE684 induced cleavage of PARP, a characteristic of apoptosis, in H3122 cells as well as in 3T3/EAV1 and 3T3/EAV3 cells (Fig. 4A). TAE684 also increased the abundance of BIM, a proapoptotic member of the Bcl-2 family of proteins, in cells expressing EML4-ALK, whereas the amounts of the Bcl-2 family members Mcl-1 and Bcl-xL remained unaffected (Fig. 4A). In contrast, TAE684 induced downregulation of the expression of survivin, a member of the IAP family, in cells expressing EML4-ALK, whereas the expression of XIAP, another IAP family member, remained unaffected (Fig. 4A). To investigate the possible roles of the ERK and STAT3 signaling pathways in the induction of BIM and downregulation of survivin by TAE684, we examined the effects of EML4-ALK, ERK, or STAT3 depletion by RNAi in 3T3/EAV1, 3T3/EAV3, and H3122 cells. Similar to the effects of TAE684 (Fig. 3C), depletion of EML4-ALK with an ALK siRNA resulted in inhibition of both ERK and STAT3 phosphorylation in all 3 cell lines (Fig. 4B). The amount of BIM was increased as a result of EML4-ALK or ERK depletion but was not affected by STAT3 depletion (Fig. 4B). In contrast, the expression of survivin was inhibited by depletion of EML4-AKT or STAT3 but not by that of ERK (Fig. 4B). Similar results were obtained with a second set of ALK, ERK, and STAT3 siRNAs targeted to different regions of the corresponding mRNAs (data not shown). These data thus suggested that ALK inhibition results in upregulation of BIM expression through inhibition of the ERK signaling pathway as well as in downregulation of survivin expression through inhibition of the STAT3 signaling pathway.

### Role of ERK-BIM and STAT3-survivin signaling pathways in TAE684-induced apoptosis in cells expressing EML4-ALK

To investigate further whether induction of BIM is related to TAE684-induced apoptosis, we transfected 3T3/EAV3 or H3122 cells with an siRNA specific for BIM mRNA. Such transfection largely blocked BIM induction by TAE684 (Fig. 5A). Staining with annexin V revealed that RNAi-mediated attenuation of BIM induction resulted in significant inhibition of TAE684-induced apoptosis in both cell lines (Fig. 5A), implicating upregulation of BIM expression in the induction of apoptosis by TAE684 in EML4-ALK–positive cells. We obtained similar results with a second siRNA targeted to a different sequence within BIM mRNA (data not shown). Given that TAE684 inhibited STAT3-survivin signaling in cells expressing EML4-ALK, we next investigated the contribution of such signaling to TAE684-induced apoptosis by transfecting 3T3/EAV3 or H3122 cells with an expression vector encoding a FLAG epitope–tagged constitutively active (CA) form of human STAT3. Expression of CA-STAT3 increased the abundance of survivin (Fig. 5B), consistent with the notion that survivin expression is upregulated by activation of STAT3 signaling. Furthermore, expression of CA-STAT3 inhibited the downregulation of survivin induced by TAE684, without affecting BIM induction (Fig. 5B), and it significantly inhibited TAE684-induced apoptosis (Fig. 5B). These data suggested that inhibition of the STAT3 signaling pathway contributes to TAE684-induced apoptosis in EML4-ALK–positive cells. To confirm that TAE684-induced apoptosis mediated by STAT3 inhibition was attributable to downregulation of survivin expression, we transfected 3T3/EAV3 or H3122 cells with an expression vector for human survivin. Survivin overexpression resulted in substantial inhibition of the TAE684-induced downregulation of survivin in both 3T3/EAV3 and H3122 cells (Fig. 5C), and this effect was associated with significant inhibition

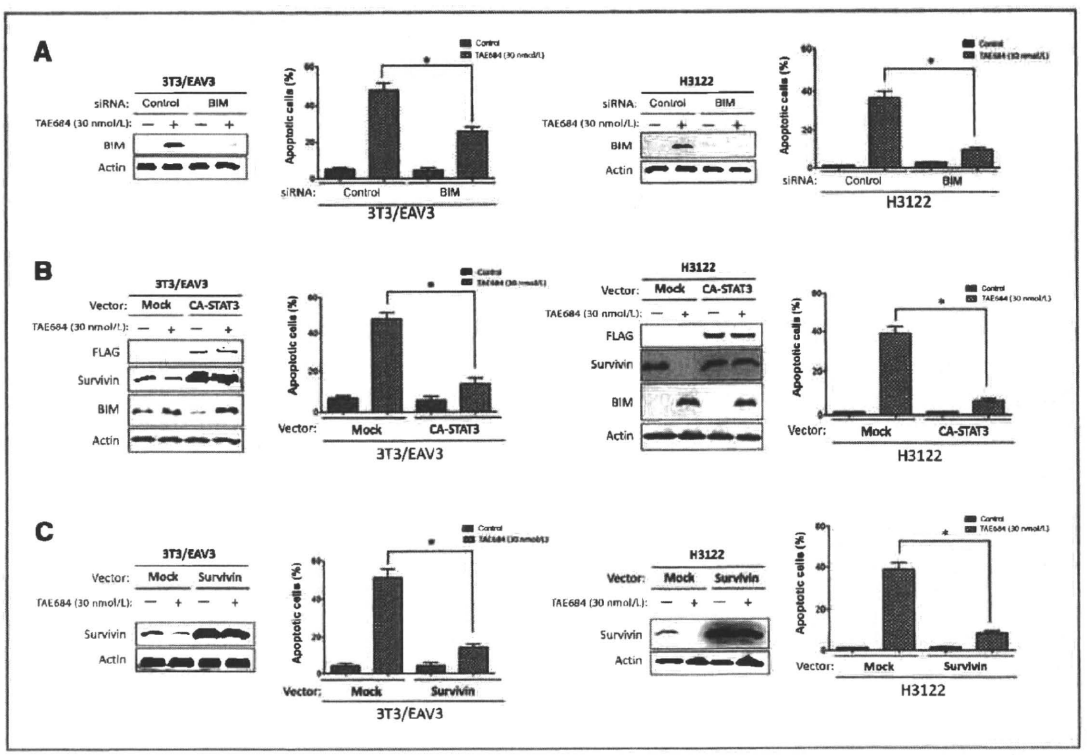


Figure 5. Effects of BIM depletion as well as forced expression of CA-STAT3 and survivin on apoptosis induced by TAE684 in 3T3/EAV3 or H3122 cells. A, cells were transfected with nonspecific (control) or BIM siRNAs for 24 hours and then incubated in complete medium with 30 nmol/L TAE684 or DMSO vehicle for 48 hours, after which cells either were lysed and subjected to immunoblot analysis with antibodies to the indicated proteins or were evaluated for apoptosis by staining with annexin V and PI followed by flow cytometry. B, cells were transfected with an expression vector for FLAG-tagged CA-STAT3 or with the corresponding empty vector for 24 hours and were then incubated with or without 30 nmol/L TAE684 for 48 hours and analyzed as in A. C, cells were transfected with an expression vector for survivin or with the corresponding empty vector for 24 hours and were then incubated with or without 30 nmol/L TAE684 for 48 hours and analyzed as in A. All quantitative data are means ± SD from at least 3 independent experiments. *, $P < 0.05$ for the indicated comparisons.

of TAE684-induced apoptosis (Fig. 5C). These results thus suggested that inhibition of STAT3-survivin signaling by TAE684 contributes substantially to the induction of apoptosis by this drug. Collectively, our results thus suggested that inhibition of both the ERK-BIM and STAT3-survivin signaling pathways contributes to the induction of apoptosis associated with ALK inhibition in EML4-ALK–positive lung cancer cells.

## Discussion

*EML4-ALK* was only recently identified as a transforming fusion gene in NSCLC (4). Although EML4-ALK was shown to possess marked oncogenic activity both *in vitro* and *in vivo* (4, 15), the signaling pathways underlying malignant transformation by the fusion protein have remained unclear. We have now shown that phosphorylation of both ERK and STAT3 was similarly and markedly increased in NIH 3T3 cells by forced expression of either variant 1 or variant 3 of EML4-ALK, whereas phosphorylation of AKT remained unaffected. Similar effects were observed in different clones of these cells stably transfected with a vector for either variant of EML4-ALK (data not shown). We further showed that the growth of both 3T3/EAV1 and 3T3/EAV3 cells was significantly attenuated by inhibition of ERK or STAT3 signaling but not by that of PI3K signaling. NPM-ALK has also been shown to activate ERK and STAT3 signaling pathways (6, 27–33), both of which are thought to be essential downstream mediators of the oncogenic action of NPM-ALK. In the present study, we found that ALK siRNA markedly abrogated the phosphorylation of AKT in the NPM-ALK–positive lymphoma cell line Karpas299, consistent with previous results implicating activation of PI3K-AKT signaling in malignant transformation by NPM-ALK (22–25). In contrast, we found that ALK siRNA did not suppress AKT phosphorylation in the EML4-ALK–positive lung cancer cell line H3122. Together, our results thus suggest that both ERK and STAT3 signaling pathways, rather than the PI3K signaling pathway, are the principal downstream pathways activated by EML4-ALK in lung cancer cells. Oncogenic ALK fusion proteins therefore may activate downstream pathways in a manner dependent on the fusion partner (Supplementary Fig. S1).

Preclinical studies have shown that treatment of NSCLC cell lines expressing EML4-ALK with ALK inhibitors suppresses cell proliferation and induces apoptosis (9, 34), although the underlying mechanisms of these effects were not well characterized. We have now shown that TAE684, a specific inhibitor of the kinase activity of ALK, significantly inhibited the phosphorylation of ERK and STAT3, but not that of AKT, in EML4-ALK positive lung cancer cells, supporting the notion that ERK and STAT3 signaling pathways function downstream of EML4-ALK. BIM is a key proapoptotic member of the Bcl-2 family of proteins and initiates apoptosis signaling by binding to and antagonizing the function of prosurvival members of the Bcl-2 family (35). We found that TAE684 induced upregulation of BIM in EML4-ALK–positive lung cancer cells. With the use of RNAi-mediated depletion of ERK, we also found that BIM expression is regulated by the ERK signaling pathway. We further showed that knockdown of BIM by RNAi resulted in significant inhibition of TAE684-induced apoptosis in EML4-ALK–positive cells, suggesting that BIM induction mediated by inhibition of the ERK pathway plays a pivotal role in ALK inhibitor–induced apoptosis in EML4-ALK–positive lung cancer cells. These findings are consistent with the previous observation that inhibition of the ERK pathway contributes to EGFR-TKI–induced BIM upregulation, which is essential for the induction of apoptosis by these agents, in *EGFR* mutation–positive NSCLC cells (36–38).

Survivin is a member of the IAP family and protects against apoptosis by either directly or indirectly inhibiting the activation of effector caspases (39). We have now shown that TAE684 inhibited the expression of survivin in EML4-ALK–positive lung cancer cells. Furthermore, depletion of STAT3 resulted in downregulation of survivin expression, whereas expression of a constitutively active form of STAT3 resulted in upregulation of survivin expression. These data indicate that expression of survivin is regulated primarily through the STAT3 signaling pathway, consistent with the results of a previous study (40). We further found that expression of CA-STAT3 blocked the TAE684-induced downregulation of survivin, indicating that ALK inhibition results in survivin downregulation through inhibition of the STAT3 signaling pathway. Forced expression of either CA-STAT3 or survivin attenuated TAE684-induced apoptosis in 3T3/EAV3 or H3122 cells, suggesting that inhibition of STAT3-survivin signaling contributes to ALK inhibitor–induced apoptosis in EML4-ALK–positive lung cancer cells. Our present data thus suggest that ALK inhibitor–induced apoptosis is mediated both by upregulation of BIM through inhibition of the ERK pathway and by downregulation of survivin through inhibition of the STAT3 pathway in EML4-ALK–positive lung cancer cells.

In conclusion, our results have identified both ERK and STAT3 signaling pathways as key mediators of the transforming activity of EML4-ALK in lung cancer cells positive for this fusion protein. We further demonstrated that inhibition of both ERK-BIM and STAT3-survivin signaling pathways is responsible for ALK inhibitor–induced apoptosis in these cells. Our results thus provide a basis for the further development of ALK-targeted therapy in EML4-ALK–positive lung cancer patients.

## Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

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Received October 19, 2010; revised January 20, 2011; accepted February 10, 2011; published OnlineFirst.

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Oncogene (2011) 1–10
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ORIGINAL ARTICLE

# Roles of BIM induction and survivin downregulation in lapatinib-induced apoptosis in breast cancer cells with *HER2* amplification

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**Lapatinib, a dual tyrosine kinase inhibitor of the epidermal growth factor receptor and human epidermal growth factor receptor 2 (HER2), is clinically active in patients with breast cancer positive for *HER2* amplification. The mechanism of this anti-tumor action has remained unclear, however. We have now investigated the effects of lapatinib in *HER2* amplification-positive breast cancer cells with or without an activating *PIK3CA* mutation. Lapatinib induced apoptosis in association with upregulation of the pro-apoptotic protein BIM through inhibition of the MEK-ERK signaling pathway in breast cancer cells with *HER2* amplification. RNA interference (RNAi)-mediated depletion of BIM inhibited lapatinib-induced apoptosis, implicating BIM induction in this process. The pro-apoptotic effect of lapatinib was less pronounced in cells with a *PIK3CA* mutation than in those without one. Lapatinib failed to inhibit AKT phosphorylation in *PIK3CA* mutant cells, likely because of hyperactivation of the phosphatidylinositol 3-kinase (PI3K) signaling pathway by the mutation. Depletion of PIK3CA (a catalytic subunit of PI3K) revealed that survivin expression is regulated by the PI3K pathway in these cells, suggesting that insufficient inhibition of PI3K-survivin signaling is responsible for the limited pro-apoptotic effect of lapatinib in *HER2* amplification-positive cells with a *PIK3CA* mutation. Consistent with this notion, depletion of survivin by RNAi or treatment with a PI3K inhibitor markedly increased the level of apoptosis in *PIK3CA* mutant cells treated with lapatinib. Our results thus suggest that inhibition of both PI3K-survivin and MEK-ERK-BIM pathways is required for effective induction of apoptosis in breast cancer cells with *HER2* amplification.**

*Oncogene* (2011) **0,** 000–000. doi:10.1038/onc.2011.111

**Keywords:** BIM; survivin; *HER2* amplification; *PIK3CA* mutation; apoptosis; breast cancer

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Received 3 October 2010; revised 17 February 2011; accepted 1 March 2011

## Introduction

Breast cancer is the leading cause of cancer death among women worldwide. Amplification of the human epidermal growth factor receptor 2 (*HER2*) gene occurs in 25–30% of breast cancers (Slamon *et al.*, 1987, 1989), and HER2 is thus an attractive target for the development of therapeutic drugs. Lapatinib, a dual tyrosine kinase inhibitor of HER2 and the epidermal growth factor receptor (EGFR), has shown anti-tumor activity for breast cancer with *HER2* amplification in pre-clinical and clinical studies (Geyer *et al.*, 2006; Konecny *et al.*, 2006; Gomez *et al.*, 2008). Although lapatinib improved the overall outcome for such patients, not all patients were benefited from the treatment. Characterization of the molecular basis of the response to lapatinib will thus be important to maximize the clinical efficacy of this drug.

Mutations in *PIK3CA*, which encodes the p110α catalytic subunit of phosphatidylinositol 3-kinase (PI3K), have been identified in 8–40% of breast cancers (Samuels *et al.*, 2004; Saal *et al.*, 2005; Berns *et al.*, 2007). Although a positive correlation between HER2 overexpression and the presence of *PIK3CA* mutations has been described (Saal *et al.*, 2005), the relation between the efficacy of lapatinib and such mutations has remained unclear (Eichhorn *et al.*, 2008; Toi *et al.*, 2009; Kataoka *et al.*, 2010). We have therefore now investigated the effects of lapatinib in *HER2* amplification-positive breast cancer cells with or without an activating *PIK3CA* mutation, and we further examined the mechanism responsible for the induction of apoptosis in these cells.

## Results

*Lapatinib inhibits cell proliferation and induces apoptosis in breast cancer cells with* HER2 *amplification*

We first examined the effect of lapatinib on the proliferation *in vitro* of breast cancer cells positive or negative for *HER2* amplification (Figure 1a). All six cell lines with *HER2* amplification, including SK-BR3, ZR-75-30, BT-474, MB-361, MB-453 and HCC1954, were sensitive to lapatinib, with median inhibitory concentration ($IC_{50}$) values ranging from 0.05 to 0.80 μM, which are within the clinically achievable concentration range

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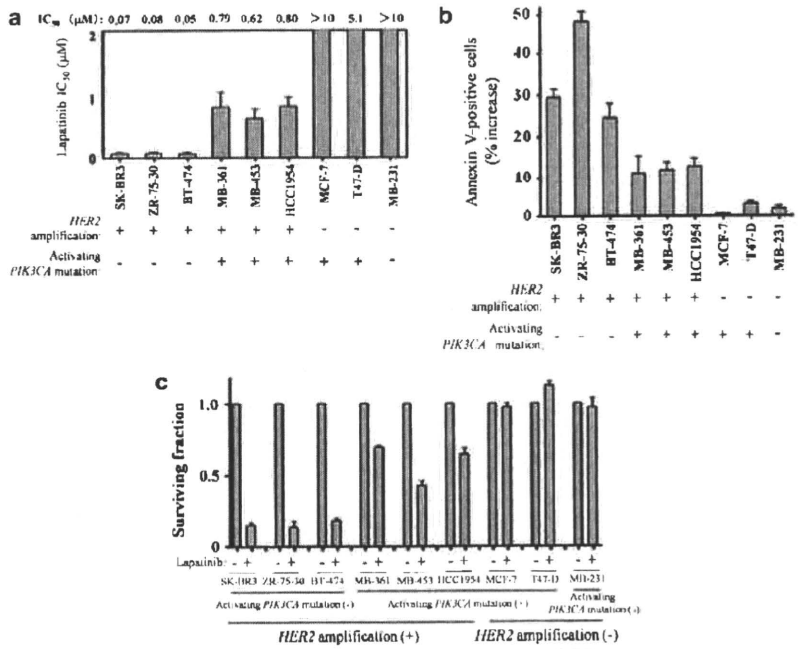


**Figure 1** Effects of lapatinib on cell proliferation and apoptosis in breast cancer cells classified according to *HER2* and *PIK3CA* status. (**a**) The indicated cell lines were cultured for 72 h in complete culture medium containing various concentrations of lapatinib, after which the number of viable cells was determined and the $IC_{50}$ value of lapatinib for inhibition of cell proliferation was calculated. (**b**) The indicated cell lines were incubated for 72 h with lapatinib (1 μM), after which the number of apoptotic cells was determined by staining with annexin V and propidium iodide followed by flow cytometry. The percentage increase in the number of apoptotic cells relative to the corresponding value for cells incubated without lapatinib is shown. (**c**) The indicated cell lines were cultured for 14 days in the presence of lapatinib (1 μM) before determination of the number of colonies for calculation of the surviving fraction relative to that of control cells incubated without lapatinib. All data are means ± s.e. from three independent experiments.

for this drug (LoRusso *et al*., 2008; Burris *et al*., 2009). Among these *HER2* amplification-positive cells, those with an activating *PIK3CA* mutation (MB-361, MB-453 and HCC1954) were less sensitive to lapatinib than were those without such a mutation (SK-BR3, ZR-75-30 and BT-474). Cell lines negative for *HER2* amplification, including MCF-7, T47-D and MB-231, were resistant to lapatinib, with $IC_{50}$ values of $>5.0\,\mu M$.

We next examined the effect of lapatinib on apoptosis in these various breast cancer cell lines (Figure 1b). An annexin V binding assay showed that lapatinib (1 μM) induced apoptosis in all *HER2* amplification-positive cells, but was largely without effect in amplification-negative cells. Consistent with the $IC_{50}$ values for the anti-proliferative effect of the drug, the extent of lapatinib-induced apoptosis was less pronounced in *HER2* amplification-positive cells with an activating *PIK3CA* mutation than in those without such a mutation. We further examined the effect of lapatinib on clonogenic survival of breast cancer cells. Again, lapatinib greatly reduced the clonogenicity of *HER2* amplification-positive cells without a *PIK3CA* mutation, whereas the reduction in the number of clones was less marked for those with a *PIK3CA* mutation (Figure 1c). These data thus revealed that lapatinib exerts anti-proliferative and anti-survival effects in cells positive for *HER2* amplification, but the extent of these effects is smaller for such cells with a *PIK3CA* mutation than for those without this genetic change.

### *Differential effect of lapatinib on AKT signaling in* HER2 *amplification-positive breast cancer cells with or without an activating* PIK3CA *mutation*

We examined the effects of lapatinib on the AKT and ERK (extracellular signal-regulated kinase) signaling pathways in breast cancer cell lines (Figure 2a). Immunoblot analysis showed that phosphorylation of both AKT and ERK was markedly inhibited by lapatinib in *HER2* amplification-positive cells without an activating *PIK3CA* mutation. In *HER2* amplification-positive cells harboring a *PIK3CA* mutation, however, lapatinib inhibited the phosphorylation of ERK but had little effect on that of AKT. Lapatinib showed little effect on the phosphorylation of AKT or ERK in *HER2* amplification-negative cells. These data thus revealed that, whereas lapatinib inhibited the phosphorylation of ERK in all *HER2* amplification-positive cells, its effect on that of AKT was dependent on *PIK3CA* mutational status.

### *Effects of lapatinib on apoptosis-related proteins in* HER2 *amplification-positive breast cancer cells with or without an activating* PIK3CA *mutation*

Given that lapatinib induced apoptosis in cells with *HER2* amplification, we examined its effects on apoptosis-related proteins in these cells (Figure 2b). Immunoblot analysis revealed that lapatinib upregulated the expression of BIM, a pro-apoptotic member of the Bcl-2

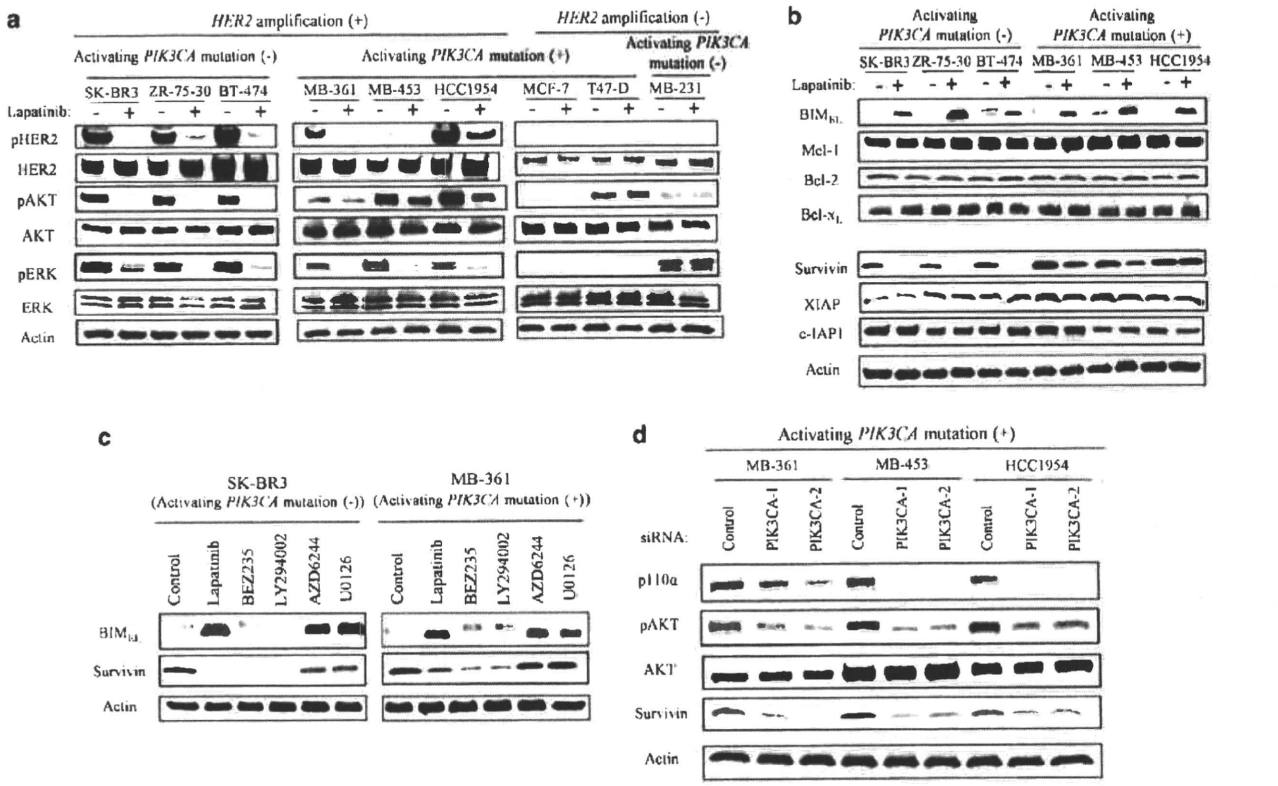


**Figure 2** Effects of lapatinib on HER2, AKT and ERK phosphorylation as well as on apoptosis-related protein expression in breast cancer cell lines. (**a**, **b**) The indicated cell lines were incubated with or without lapatinib (1 μM) for 24 h (**a**) or 48 h (**b**), after which cell lysates were prepared and subjected to immunoblot analysis with antibodies to phosphorylated (p) or total forms of HER2, AKT or ERK as well as with those to the indicated apoptosis-related proteins or to β-actin (loading control). The position of the band corresponding to $BIM_{EL}$ is indicated. (**c**) SK-BR3 or MB-361 cells were incubated in the absence (control, 0.1% dimethyl sulfoxide) or presence of lapatinib (1 μM), BEZ235 (0.3 μM), LY294002 (20 μM), AZD6244 (0.3 μM) or U0126 (20 μM) for 48 h, after which cell lysates were prepared and subjected to immunoblot analysis with antibodies to BIM, to survivin or to β-actin. (**d**) The indicated cell lines were transfected with non-specific (control), PIK3CA-1 or PIK3CA-2 siRNAs for 48 h, after which cell lysates were prepared and subjected to immunoblot analysis with antibodies to the indicated proteins.

family of proteins, in *HER2* amplification-positive cells regardless of the *PIK3CA* mutational status, whereas it had little effect on the expression of other Bcl-2 family members, including Mcl-1, Bcl-2 and Bcl-$x_L$. Quantitative reverse transcription and PCR analysis showed that lapatinib increased the amount of BIM mRNA in all *HER2* amplification-positive cells in a manner independent of the *PIK3CA* mutational status (Supplementary Figure 1), suggesting that BIM induction by lapatinib is mediated at the transcriptional level. On the other hand, lapatinib downregulated the expression of survivin, a member of the inhibitor of apoptosis protein (IAP) family, in *HER2* amplification-positive cells without an activating *PIK3CA* mutation but not in those with such a mutation. The expression of other IAP family members, including XIAP and c-IAP1, was not substantially affected by lapatinib in any of the cell lines examined.

To identify the signaling pathways responsible for induction of BIM and downregulation of survivin by lapatinib, we examined the effects of specific inhibitors of PI3K (BEZ235 and LY294002) and of the ERK kinase MEK (AZD6244 and U0126). Each of the MEK inhibitors induced BIM expression without affecting the expression of survivin in *HER2* amplification-positive cells regardless of the *PIK3CA* mutational status (Figure 2c), suggesting that expression of BIM is regulated by the MEK-ERK pathway. Conversely, the PI3K inhibitors reduced the abundance of survivin without affecting that of BIM in all cells with *HER2* amplification (Figure 2c). We further examined the effect of depletion of PIK3CA (p110α) by RNA interference (RNAi) on survivin expression in *PIK3CA* mutant cells. Introduction of two independent small interfering RNAs (siRNAs) specific for PIK3CA mRNA (PIK3CA-1 and PIK3CA-2 siRNAs) into *HER2* amplification-positive cells with an activating *PIK3CA* mutation, resulted in a marked decrease in the expression of p110α and a concomitant decrease in the level of AKT phosphorylation. This depletion of p110α was also associated with downregulation of survivin expression in these cell lines (Figure 2d), suggesting that survivin expression was regulated through the PI3K pathway. Together, these data suggested that lapatinib induced BIM expression through inhibition of the MEK-ERK pathway in *HER2* amplification-positive

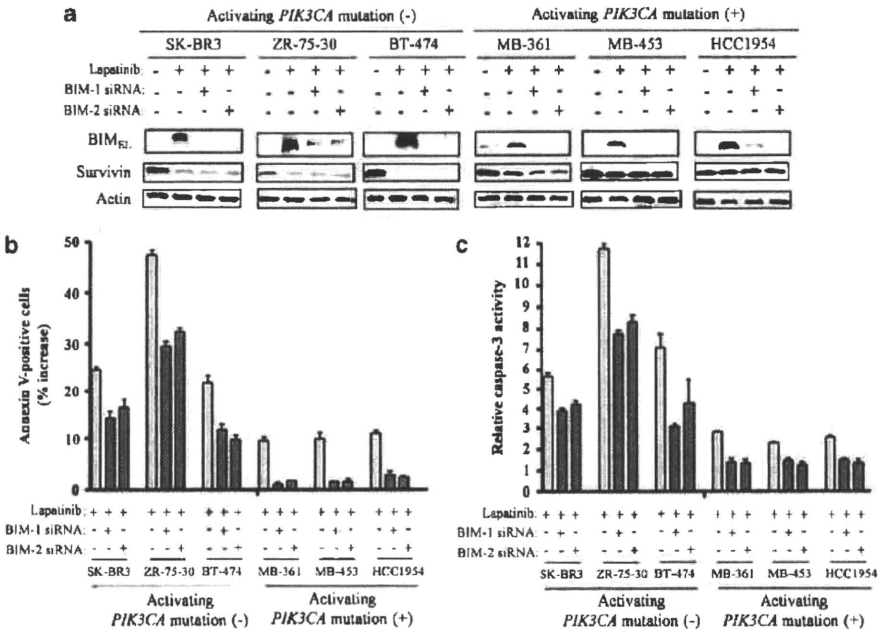


**Figure 3** Effect of inhibition of BIM induction on lapatinib-induced apoptosis in *HER2* amplification-positive breast cancer cells with or without an activating *PIK3CA* mutation. (**a**) The indicated cell lines were transfected with BIM-1, BIM-2 or non-specific siRNAs for 24 h and then incubated for 48 h in complete medium with or without lapatinib (1 μM). Cell lysates were then prepared and subjected to immunoblot analysis with antibodies to BIM, to survivin or to β-actin. (**b**) Cells transfected as in a were incubated for 72 h with or without lapatinib (1 μM), and then evaluated for the proportion of apoptotic cells by staining with annexin V and propidium iodide followed by flow cytometry. The percentage increase in the number of apoptotic cells relative to the corresponding value for cells transfected with the control siRNA and incubated without lapatinib is shown. (**c**) Lysates prepared from cells treated as in (**a**) were assayed for caspase-3 activity, which is expressed relative to the corresponding value for cells transfected with the control siRNA and incubated without lapatinib. Data in b and c are means ± s.e. from three independent experiments.

cells with or without an activating *PIK3CA* mutation. On the other hand, lapatinib downregulated survivin expression through inhibition of the PI3K signaling pathway in *HER2* amplification-positive cells without a *PIK3CA* mutation, but it had little effect on survivin expression in cells with such a mutation, likely as a result of activation of the PI3K pathway by the *PIK3CA* mutation.

*Effect of inhibition of BIM induction on lapatinib-induced apoptosis in cells with* HER2 *amplification*

To investigate the role of BIM induction in lapatinib-induced apoptosis, we transfected *HER2* amplification-positive cells with two independent siRNAs specific for BIM mRNA (BIM-1 and BIM-2 siRNAs). Each BIM siRNA markedly suppressed the lapatinib-induced upregulation of BIM without affecting lapatinib-induced downregulation of survivin (Figure 3a). The annexin V binding assay showed that such transfection resulted in partial inhibition of lapatinib-induced apoptosis in *HER2* amplification-positive cells without an activating *PIK3CA* mutation, whereas lapatinib-induced apoptosis was almost completely inhibited by BIM siRNA in cells with such a mutation (Figure 3b). Similar to the results of the annexin V binding assay, transfection with BIM siRNA resulted in partial inhibition of the lapatinib-induced activation of caspase-3 in cells without a *PIK3CA* mutation, whereas it resulted in almost complete inhibition of this effect of lapatinib in cells with a *PIK3CA* mutation (Figure 3c). The BH3-mimetic ABT737, which binds to anti-apoptotic Bcl-2 family members, including Bcl-2, Bcl-xl and Bcl-w, was shown to enhance apoptosis under conditions of BIM induction (Cragg *et al.*, 2007, 2008; Gong *et al.*, 2007). We therefore examined the effect of the combination of lapatinib and ABT737 on induction of apoptosis in *HER2*-amplified breast cancer cells with or without a *PIK3CA* mutation. We found that ABT737 enhanced lapatinib-induced apoptosis both in HER2-positive cells without a *PIK3CA* mutation, and in those with a *PIK3CA* mutation with an average fold increase of 1.20 and 1.48, respectively ($P<0.05$) (Supplementary Figure 2), supporting a role for BIM induction in lapatinib-induced apoptosis. These data thus indicated that BIM induction contributes to lapatinib-induced apoptosis in cells with *HER2* amplification, but that the extent of this contribution differs according to the mutational status of *PIK3CA*.

*Combined effect of lapatinib and BEZ235 on apoptosis in* HER2 *amplification-positive cells with an activating* PIK3CA *mutation*

Given that lapatinib manifested only a moderate pro-apoptotic effect in cells with an activating *PIK3CA*

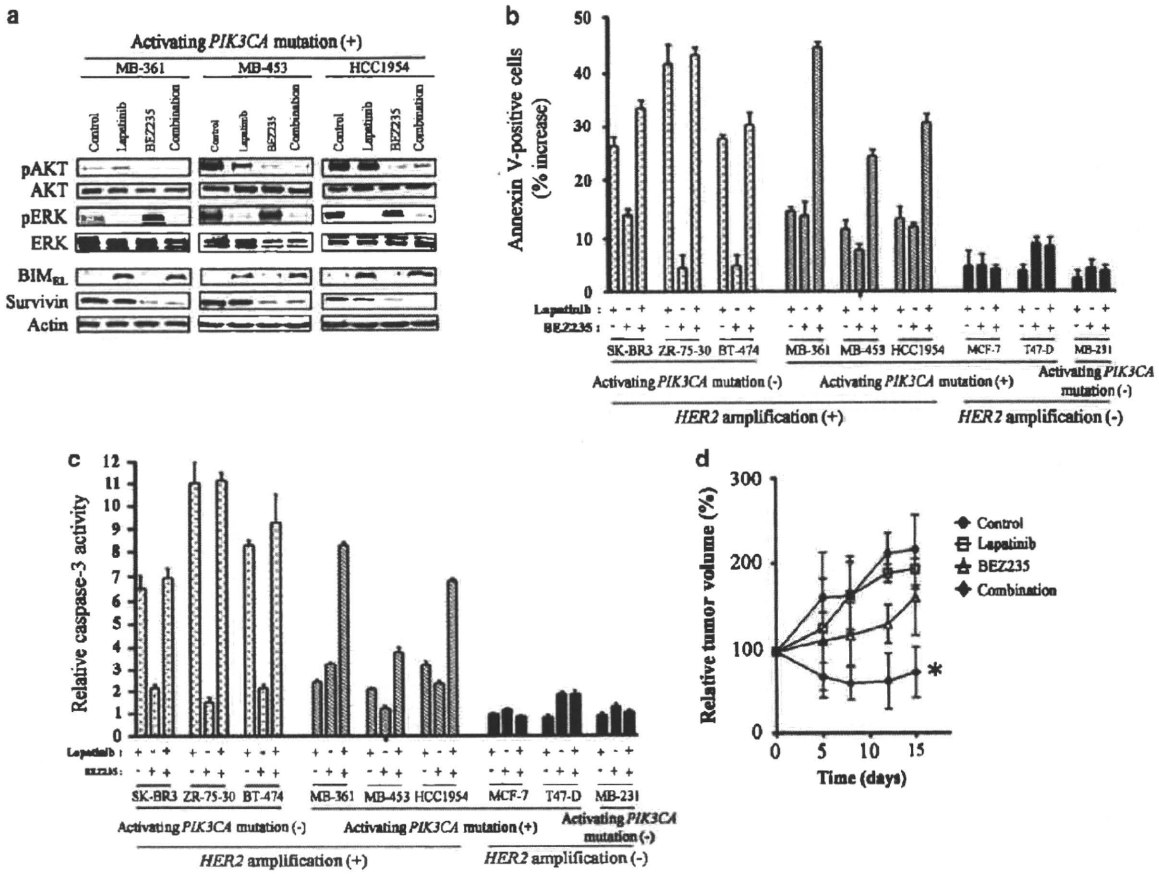


**Figure 4** Effects of the combination of BEZ235 and lapatinib in *HER2* amplification-positive cells with an activating *PIK3CA* mutation. (**a**) The indicated cell lines were incubated in the absence (control, 0.1% dimethyl sulfoxide) or presence of lapatinib (1 μM), BEZ235 (0.03 μM) or both agents (combination) for 48 h, after which cell lysates were prepared and subjected to immunoblot analysis with antibodies to the indicated proteins. (**b**) Cells were incubated in the absence or presence of lapatinib (1 μM) or BEZ235 (0.03 μM), as indicated, for 72 h, after which the proportion of apoptotic cells was determined by staining with annexin V and propidium iodide followed by flow cytometry. The percentage increase in the number of apoptotic cells relative to the corresponding value for cells incubated without addition is shown. (**c**) Cells treated as in (**a**) were lysed and assayed for caspase-3 activity, which is expressed relative to the corresponding value for cells incubated without addition. Data in (**b**, **c**) are means ± s.e. from three independent experiments. (**d**) Nude mice with tumor xenografts established by subcutaneous injection of HCC1954 cells were treated daily for 2 weeks with vehicle (control), BEZ235 (15 mg/kg per day), lapatinib (100 mg/kg per day) or the combination of both drugs. Tumor size was determined at the indicated times after treatment onset and is expressed as a percentage of that at time 0. Data are means ± s.e. for six mice per group. $^*P<0.05$ for the combination of BEZ235 and lapatinib versus either BEZ235 or lapatinib alone.

mutation despite the preserved induction of BIM, we hypothesized that insufficient inhibition of the PI3K pathway by lapatinib might be responsible for the limited size of this effect compared with that observed in cells without such a mutation. We therefore examined whether additional inhibition of the PI3K pathway by BEZ235 might enhance the effect of lapatinib on apoptosis in *PIK3CA* mutant cells. Treatment with BEZ235, which was previously shown to inhibit the PI3K pathway in cells expressing activated PIK3CA (Serra *et al*., 2008; Brachmann *et al*., 2009), resulted in marked inhibition of AKT phosphorylation (but not of ERK phosphorylation) in *HER2* amplification-positive cells with an activating *PIK3CA* mutation (Figure 4a). The combination of BEZ235 and lapatinib resulted in inhibition of both AKT and ERK phosphorylation (Figure 4a). Consistent with the notion that regulation of survivin is mediated through the PI3K pathway and that of BIM is mediated through the MEK-ERK pathway, treatment with BEZ235 alone induced downregulation of survivin expression without affecting BIM expression, whereas the combination of BEZ235 and lapatinib elicited both survivin downregulation and BIM upregulation (Figure 4a). The combination of BEZ235 and lapatinib increased the number of apoptotic cells to an extent markedly greater than that apparent with either agent alone in *HER2* amplification-positive cells with a *PIK3CA* mutation, whereas the effect of lapatinib was similar in the absence or presence of BEZ235 in those without a *PIK3CA* mutation or in cells negative for *HER2* amplification (Figure 4b). A similar pattern was observed for the effects of lapatinib and

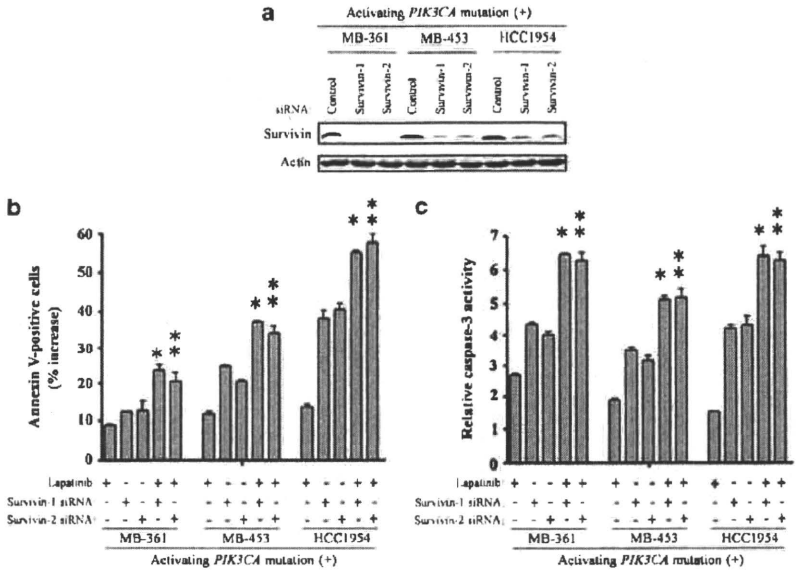


**Figure 5** Effect of survivin depletion on apoptosis in *HER2* amplification-positive cells with an activating *PIK3CA* mutation. (**a**) The indicated cell lines were transfected with non-specific (control), survivin-1 or survivin-2 siRNAs for 48 h, after which cell lysates were prepared and subjected to immunoblot analysis with antibodies to survivin or to β-actin. (**b**) Cells transfected as in (**a**) were incubated in complete medium with or without lapatinib (1 μM) for 72 h, after which the proportion of apoptotic cells was determined by staining with annexin V and propidium iodide followed by flow cytometry. The percentage increase in the number of apoptotic cells relative to the corresponding value for cells transfected with the control siRNA and incubated without lapatinib is shown. (**c**) Cells transfected as in (**a**) were incubated with or without lapatinib (1 μM) for 48 h, lysed and assayed for caspase-3 activity, which is expressed relative to the corresponding value for cells transfected with the control siRNA and incubated without lapatinib. Data in (**b**, **c**) are means ± s.e. from three independent experiments. $*P<0.05$ for the combination of lapatinib plus transfection with survivin-1 siRNA versus either treatment alone. $**P<0.05$ for the combination of lapatinib plus transfection with survivin-2 siRNA versus either treatment alone.

BEZ235 on caspase-3 activity (Figure 4c). We further examined the effect of combined treatment with BEZ235 and lapatinib on the growth *in vivo* of *HER2* amplification-positive breast cancer cells with a *PIK3CA* mutation. At the completion of the experiments, tumors treated with either control or lapatinib alone had doubled in size, whereas the combination of lapatinib and BEZ235 maintained tumor regression ($P<0.05$) (Figure 4d), consistent with the combined effect of these agents observed in our *in vitro* experiments. All treatments were well tolerated by the mice, with no signs of toxicity or weight loss during therapy (data not shown). These results thus suggested that effective inhibition of the PI3K pathway and lapatinib treatment cooperate to elicit a substantial level of apoptosis that is accompanied by BIM induction and survivin downregulation in *HER2* amplification-positive cells with an activating *PIK3CA* mutation.

*Combined effect of lapatinib and depletion of survivin on apoptosis in* HER2 *amplification-positive cells with an activating* PIK3CA *mutation*

Finally, to investigate the effect of downregulation of survivin expression on apoptosis in *HER2* amplification-positive cells with an activating *PIK3CA* mutation, we depleted such cells of survivin by RNAi (Figure 5a). Each of two independent survivin siRNAs induced apoptosis in these cells, whereas the combination of survivin depletion and lapatinib increased the number of apoptotic cells to an extent significantly greater than that observed with either treatment alone (Figure 5b). These effects on the number of apoptotic cells were confirmed by measurement of caspase-3 activity (Figure 5c). These data thus suggested that downregulation of survivin itself has a pro-apoptotic effect in cells with a *PIK3CA* mutation, but that survivin depletion and lapatinib cooperate to induce an enhanced level of apoptosis.

## Discussion

*HER2* amplification is a frequent molecular abnormality in breast cancer, and is associated with a poor outcome and aggressiveness of the disease (Slamon *et al.*, 1987, 1989). Lapatinib, a dual tyrosine kinase inhibitor of EGFR and HER2, shows anti-tumor activity in HER2-overexpressing breast cancer (Geyer *et al.*, 2006; Konecny *et al.*, 2006; Gomez *et al.*, 2008), but the precise mechanism of its anti-tumor effect has remained unclear. We have now investigated the downstream mediators of lapatinib-induced apoptosis in breast cancer cells with *HER2* amplification. BIM is a key pro-apoptotic member of the Bcl-2 family of proteins,

and initiates apoptosis signaling by binding to and antagonizing the function of pro-survival Bcl-2 family members (Chen *et al.*, 2005). Our results indicate that lapatinib induces upregulation of BIM expression in *HER2* amplification-positive cells, and that depletion of BIM by RNAi results in marked inhibition of lapatinib-induced apoptosis in these cells. These data suggest that upregulation of BIM expression contributes to the induction of apoptosis by lapatinib in breast cancer cells with *HER2* amplification. We found that BIM induction by lapatinib occurred in *HER2* amplification-positive cells regardless of *PIK3CA* mutational status and was associated with inhibition of ERK phosphorylation. With the use of specific inhibitors of MEK, we also found that regulation of BIM expression is mediated by the MEK-ERK signaling pathway. These findings are consistent with those of previous studies showing that MEK inhibitors induce BIM expression in B-RAF mutant cells (Cragg *et al.*, 2008), and that inhibition of the MEK-ERK pathway contributes to BIM induction by EGFR tyrosine kinase inhibitors in non-small cell lung cancer (Costa *et al.*, 2007; Cragg *et al.*, 2007; Gong *et al.*, 2007), and that such upregulation of BIM has an essential role in the induction of apoptosis by these agents. We also found that ABT737 enhanced the induction of apoptosis by lapatinib in cells with *HER2* amplification regardless of *PIK3CA* mutational status, further supporting a role for BIM induction in lapatinib-induced apoptosis. To our knowledge, the present study is the first to show that induction of BIM through inhibition of the MEK-ERK pathway is required for lapatinib-induced apoptosis in breast cancer with *HER2* amplification.

Although lapatinib-induced upregulation of BIM expression occurred in a manner independent of *PIK3CA* mutational status, the pro-apoptotic effect of lapatinib was less pronounced in cells with an activating *PIK3CA* mutation than in those without one. Given that such *PIK3CA* mutations result in hyperactivation of the PI3K signaling pathway (Isakoff *et al.*, 2005; Zhao *et al.*, 2005; Berns *et al.*, 2007), we examined whether activation of this pathway was associated with this difference in the extent of apoptosis. Indeed, we found that lapatinib did not inhibit the phosphorylation of AKT in *HER2* amplification-positive cells with an activating *PIK3CA* mutation. We therefore examined the effect of specific inhibitors of the PI3K pathway on lapatinib-induced apoptosis in cells with a *PIK3CA* mutation. Treatment with BEZ235 effectively inhibited AKT phosphorylation, and the combination of BEZ235 and lapatinib thus inhibited both AKT and ERK phosphorylation and had a pro-apoptotic effect that was markedly greater than that observed with either agent alone. Consistent with these *in vitro* experiments, the combination of lapatinib and BEZ235 exhibits an enhanced anti-tumor effect *in vivo* with HER2-positive xenografts with a *PIK3CA* mutation. These results suggest that additional inhibition of the PI3K pathway is required for effective induction of apoptosis by lapatinib in cells with a *PIK3CA* mutation. Lapatinib shows clinical efficacy both alone and in combination with chemotherapeutic agents, but not all patients with *HER2* amplification-positive tumors respond to such treatment (Slamon *et al.*, 1987; Slamon, 1990; Geyer *et al.*, 2006; Di Leo *et al.*, 2008; Gomez *et al.*, 2008). *PIK3CA* mutations have been detected in 20–30% of breast cancer patients with *HER2* amplification (Saal *et al.*, 2005; Stemke-Hale *et al.*, 2008), and our data now suggest that activation of the PI3K signaling pathway associated with the presence of a *PIK3CA* mutation may be responsible, at least in part, for the limited efficacy of lapatinib in patients with tumors positive for both *HER2* amplification and a *PIK3CA* mutation. Similar to the effects of lapatinib, the MEK inhibitor AZD6244 inhibited ERK phosphorylation and increased BIM expression, without affecting AKT phosphorylation or survivin expression, and it cooperated with BEZ235 to induce apoptosis in *HER2* amplification-positive cells with a *PIK3CA* mutation (Supplementary Figure 3). These data thus indicate the importance of simultaneous interruption of the PI3K-survivin and MEK-ERK-BIM pathways for effective induction of apoptosis in such cells. However, the extent of apoptosis induced by AZD6244 alone or in combination with BEZ235 was less pronounced than that induced by lapatinib, suggesting that the anti-tumor effect of lapatinib in these cells is not mediated exclusively through inhibition of MEK-ERK signaling. Further investigation is thus needed to clarify the relationship of *PIK3CA* mutational status to the efficacy of lapatinib. The development of PI3K inhibitors has advanced substantially in recent years, and clinical trials of these agents alone or in combination with other anti-tumor agents are under way. Our study therefore provides a rationale for clinical evaluation of combination therapy with lapatinib and a PI3K inhibitor in breast cancer patients with *HER2* amplification and a *PIK3CA* mutation.

Survivin is essential for proper completion of various stages of cell division, with this protein having been found to contribute to centrosomal function, spindle formation and kinetochore attachment to spindle microtubules (Speliotes *et al.*, 2000; Uren *et al.*, 2000). Survivin is preferentially expressed during the mitotic phase of the cell cycle and is physically associated with the mitotic apparatus. It has also been found to be overexpressed in some tumors, with such overexpression having been associated with a poor clinical outcome (Ambrosini *et al.*, 1997; Tanaka *et al.*, 2000; Altieri, 2003). Like other members of the IAP family such as XIAP and c-IAP1, survivin contains a single BIR (baculoviral IAP repeats) domain. Molecular antagonists of survivin, including anti-sense and siRNA oligonucleotides as well as dominant negative mutants, have been shown to induce apoptosis (Olie *et al.*, 2000; Kanwar *et al.*, 2001), suggestive of an association between survivin and apoptosis. Consistent with these previous findings, we have now shown that depletion of survivin by two independent siRNAs specific for survivin mRNA increased the number of apoptotic cells and the activity of caspase-3 in *HER2* amplification-positive breast cancer cells with a *PIK3CA* mutation. With the use of siRNAs specific for PIK3CA mRNA,

we further showed that survivin expression is regulated by the PI3K signaling pathway, consistent with previous studies linking survivin expression to this signaling pathway (McKenzie *et al.*, 2010; Peirce *et al.*, 2010). Our finding that survivin downregulation through inhibition of PI3K signaling was associated with the induction of apoptosis, is consistent with the key role of this signaling pathway in cell survival. We found that lapatinib downregulated survivin expression in association with the induction of apoptosis in *HER2* amplification-positive cells without an activating *PIK3CA* mutation. In contrast, expression of survivin was not markedly affected by lapatinib in cells harboring such a *PIK3CA* mutation. We therefore examined the effect of inhibition of survivin expression on lapatinib-induced apoptosis in *PIK3CA* mutant cells. In such cells, the combination of survivin depletion by RNAi and lapatinib treatment exhibited a pro-apoptotic effect markedly greater than that observed with either approach alone, suggesting that downregulation of survivin promotes lapatinib-induced apoptosis. We also found that, unlike lapatinib, the PI3K inhibitor BEZ235 induced downregulation of survivin expression in cells with an activating *PIK3CA* mutation, suggesting that this effect contributes, at least in part, to the enhanced level of apoptosis induced by the combination of lapatinib and BEZ235. Insufficient inhibition of the PI3K-survivin pathway may thus account for the smaller pro-apoptotic effect of lapatinib in *HER2* amplification-positive cells with an activating *PIK3CA* mutation compared with that observed in those without such a mutation.

In conclusion, we have shown that both induction of BIM and inhibition of survivin have a role in lapatinib-induced apoptosis in *HER2* amplification-positive breast cancer cells. Moreover, both the PI3K-survivin pathway and the MEK-ERK-BIM pathway contribute independently to the induction of apoptosis in these cells regardless of *PIK3CA* mutational status. Our data thus show that simultaneous interruption of the PI3K-survivin and MEK-ERK-BIM pathways is required for effective induction of apoptosis in breast cancer cells with *HER2* amplification. They further provide a rationale for the development of new therapeutic strategies for patients with breast tumors positive for *HER2* amplification, including those with an activating *PIK3CA* mutation.

## Materials and methods

*Cell culture and reagents*

The human breast cancer cell lines SK-BR3, ZR-75-30, BT-474, MB-361, MB-453, HCC1954, MCF-7, T47-D and MB-231 were obtained from American Type Culture Collection (Manassas, VA, USA). SK-BR3 cells were cultured in McCoy's medium (Invitrogen, Carlsbad, CA, USA) supplemented with 10% fetal bovine serum; BT-474 cells in Dulbecco's modified Eagle's medium (Invitrogen) supplemented with 10% fetal bovine serum; MB-361, MB-453 and MB-231 cells in L15 medium (Invitrogen) supplemented with 10% fetal bovine serum; and the remaining cells in RPMI 1640 medium (Sigma, St Louis, MO, USA) supplemented with 10% fetal bovine serum. All cells were maintained under a humidified atmosphere of 5% $CO_2$ at 37 °C. Lapatinib was obtained from Sequoia Research Products (Pangbourne, UK), AZD6244 was from ShangHai Biochempartner (Shanghai, China) and LY294002 and U0126 were from Cell Signaling Technology (Danvers, MA, USA). BEZ235 was kindly provided by Novartis (Basel, Switzerland). MB-453 and HCC1954 cells were found to harbor an H1047 hotspot mutation, and MB-361 cells were found to contain an E545K hotspot mutation by sequencing of exons 9 and 20 of *PIK3CA* (Hoeflich *et al.*, 2009; Kataoka *et al.*, 2010; Saal *et al.*, 2005; Samuels *et al.*, 2004). We categorized BT-474 cells as negative for an activating *PIK3CA* mutation for this study on the basis of the demonstrated lack of transforming activity for the K111N mutation and its minimal effect on downstream signaling (Gymnopoulos *et al.*, 2007; Zhang *et al.*, 2008).

*Growth inhibition assay* in vitro

Cells were plated in 96-well flat-bottomed plates and cultured for 24 h before exposure to various concentrations of lapatinib for 72 h. TetraColor One (5 mM tetrazolium monosodium salt and 0.2 mM 1-methoxy-5-methyl phenazinium methylsulfate; Seikagaku, Tokyo, Japan) was then added to each well, and the cells were incubated for 3 h at 37 °C before measurement of absorbance at 490 nm with a Multiskan Spectrum instrument (Thermo Labsystems, Boston, MA, USA). Absorbance values were expressed as a percentage of that for untreated cells, and the concentration of lapatinib resulting in 50% growth inhibition ($IC_{50}$) was calculated.

*Annexin V binding assay*

Binding of annexin V to cells was measured with the use of an Annexin-V-FLUOS Staining Kit (Roche, Basel, Switzerland). Cells were harvested by exposure to trypsin-EDTA, washed with phosphate-buffered saline and centrifuged at 200 *g* for 5 min. The cell pellets were resuspended in 100 µl of Annexin-V-FLUOS labeling solution, incubated for 10–15 min at 15–25 °C and then analyzed for fluorescence with a flow cytometer (FACSCalibur) and Cell Quest software (Becton Dickinson, Franklin Lakes, NJ, USA).

*Clonogenicity assay*

Cells were seeded in triplicate in six-well plates and cultured for 48 h in the presence of lapatinib (1 µM) or vehicle. They were then cultured in drug-free medium for 14 days, fixed with methanol:acetic acid (10:1, v/v) and stained with crystal violet. The mean percentage cell survival relative to controls was determined from triplicate wells.

*Immunoblot analysis*

Cells were washed twice with ice-cold phosphate-buffered saline and then lysed in a solution containing 20 mM Tris-HCl (pH 7.5), 150 mM NaCl, 1 mM EDTA, 1% Triton X-100, 2.5 mM sodium pyrophosphate, 1 mM phenylmethylsulfonyl fluoride and leupeptin (1 µg/ml). The protein concentration of cell lysates was determined with a BCA protein assay kit (Thermo Fischer Scientific, Waltham, MA, USA), and equal amounts of protein were subjected to SDS–polyacrylamide gel electrophoresis on a 7.5 or 12% gel (Bio-Rad, Hercules, CA, USA). The separated proteins were transferred to a nitrocellulose membrane, which was then incubated with Blocking One solution (Nacalai Tesque, Kyoto, Japan) for 20 min at room temperature before incubation overnight at 4 °C with primary antibodies. Rabbit polyclonal antibodies to human phosphorylated HER2 (pY1248), to phosphorylated AKT, to