

# Mitogen-activated Protein/Extracellular Signal-regulated Kinase Kinase (MEK) Inhibitors Restore Anoikis Sensitivity in Human Breast Cancer Cell Lines with a Constitutively Activated Extracellular-regulated Kinase (ERK) Pathway<sup>1</sup>

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## Abstract

Anchorage-independent growth is a hallmark of oncogenic transformation. We reported that the mitogen-activated protein/extracellular signal-regulated kinase kinase (MEK) inhibitor U0126 inhibited anchorage-independent growth of Ki-ras-transformed rat fibroblasts by simultaneously blocking both extracellular signal-regulated kinase (ERK) and mammalian target of rapamycin (mTOR)-p70<sup>S6K</sup> pathways. Here, we examined the effects of U0126 on the growth of eight human breast cancer cell lines. U0126 selectively repressed anchorage-independent growth of MDA-MB231 and HBC4 cells, two lines with constitutively activated ERK. Loss of contact with substratum triggers apoptosis in many normal cell types, a phenomenon termed anoikis. U0126 sensitized MDA-MB231 and HBC4 to anoikis, *i.e.*, upon treatment with U0126, cells deprived of anchorage entered apoptosis, whereas adherent cells remained viable. Another MEK inhibitor PD98059 also induced anoikis sensitivity in MDA-MB231 cells but not in HBC4 cells. However, HBC4 cells were sensitized to anoikis when PD98059 was combined with the mTOR inhibitor rapamycin. To study the biochemical basis for induction of anoikis sensitivity, we examined the effects of the MEK inhibitors on ERK and p70<sup>S6K</sup> pathways in anchored *versus* nonanchored cells. As in Ki-ras-transformed rat fibroblasts, U0126 reduced activation of both ERK and p70<sup>S6K</sup> in MDA-MB231 and HBC4 cells, irrespective of anchorage. PD98059, in anchored cells, was more selective for the ERK pathway and did not significantly block the p70<sup>S6K</sup> pathway. Removal of anchorage substantially sensitized p70<sup>S6K</sup> to PD98059 in MDA-MB231 cells,

whereas p70<sup>S6K</sup> in suspended HBC4 cells remained fairly refractory. U0126 was either without effect or less inhibitory on p70<sup>S6K</sup> in MDA-MB453 and SKBR3, two cell lines in which anoikis sensitivity was not induced. Thus, susceptibility of the p70<sup>S6K</sup> pathway to MEK inhibitors appeared to be an important determinant of anoikis sensitivity. The results indicate that concurrent inhibition of MEK-ERK and mTOR-p70<sup>S6K</sup> pathways induces apoptosis in MDA-MB231 and HBC4 cells when cells are deprived of anchorage but not when anchored. Inhibitors of MEK-ERK and mTOR-p70<sup>S6K</sup> pathways may provide a therapeutic strategy to selectively target neoplasms proliferating at ectopic locations, with acceptable effects on normal cells in their proper tissue context.

## Introduction

Growth parameters of normal and transformed cell lines in culture differ in various aspects. Notably, whereas normal cells generally require integrin-mediated adhesion to appropriate extracellular matrix for growth and survival, tumor cells can proliferate without cell-substratum interactions. Anchorage-independent growth is the best *in vitro* correlate to tumorigenicity (1, 2), and the difference between normal and tumor cells in anchorage dependence *in vitro* likely reflects their nature *in vivo*. Survival, growth, and differentiation of normal cells are permitted only when the cells are in their proper tissue context within the organism. On the other hand, tumor cells have the competence for activity outside of their original environment.

We anticipate that compounds that reverse anchorage independence would target tumor cells growing in defiance of positional restrictions while minimally influencing normal cells in their appropriate locations. The MEK<sup>3</sup> inhibitor U0126 suppressed anchorage-independent growth of Ki-ras transformed rat fibroblasts (3). Because most malignant cancers in humans originate in epithelial tissues, we examined the effects of U0126 on growth properties of human epithelial tumor cells. Of eight breast cancer cell lines tested, U0126 inhibited anchorage-independent growth of two lines with constitutively activated ERK.

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<sup>3</sup> The abbreviations used are: MEK, mitogen-activated protein/extracellular signal-regulated kinase kinase; ERK, extracellular signal-regulated kinase; mTOR, mammalian target of rapamycin; HEMA, 2-(hydroxyethyl methacrylate); MTT, 3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyltetrazolium bromide; PI3K, phosphatidylinositol 3-kinase.

Many normal cell types, including epithelial cells, undergo apoptosis upon detachment from their proper substratum, a phenomenon termed anoikis (4–6). This process prevents displaced and shed cells from colonizing outside of their appropriate environment and is tightly controlled to maintain homeostasis and tissue integrity. In the course of malignant transformation, cells acquire resistance to anoikis. We show that U0126 inhibits anchorage-independent growth of human breast cancer cell lines by reestablishing susceptibility to anoikis. Apoptotic response was confined exclusively to nonanchored cells, and anchored cells remained viable.

In *Ki-ras*-transformed rat fibroblasts, U0126 inhibited the mTOR-p70<sup>S6K</sup> pathway in addition to the ERK pathway. Experiments with PD98059 and rapamycin suggested that restoration of the normal phenotype depended on simultaneous blockade of both ERK and p70<sup>S6K</sup> pathways. Here we present data that induction of anoikis sensitivity in human breast cancer cell lines also requires simultaneous inhibition of the two signaling pathways. Susceptibility of the p70<sup>S6K</sup> pathway to MEK inhibitors varied among the tumor cells analyzed and appeared to underlie the sensitivity to anoikis. Our data demonstrate the potential of MEK inhibitors as a means to target malignant cells growing outside of their correct tissue context and have implications for predicting efficacy of MEK inhibitors. The results also indicate that usefulness of MEK inhibitors may be overlooked if evaluated alone by growth inhibition assay on solid support.

## Materials and Methods

**Materials.** U0126 was from Promega Corp. (Madison, WI), and PD98059 and rapamycin were from Calbiochem (San Diego, CA). Concentrated stock solutions of inhibitors were prepared in DMSO. polyHEMA was from Sigma Chemical Co. (St. Louis, MO). Antibodies against ERK1 and ERK2 were from Santa Cruz Biotechnology (Santa Cruz, CA). Phosphospecific antibodies and antibodies against S6 ribosomal protein and cleaved caspase 3 were from Cell Signaling Technology (Beverly, MA). SYBR Green I was from Molecular Probes (Eugene, OR).

**Cell Culture and Measurement of Anchorage-independent Growth.** Human breast cancer cell lines MCF-7, MDA-MB453, SKBR3, and ZR75-1 were purchased from the American Type Culture Collection. BSY1, HBC4, HBC5, and MDA-MB231 were obtained from Dr. T. Yamori (Japanese Foundation for Cancer Research, Tokyo, Japan). Anchorage-independent growth was measured on polyHEMA-coated 96-well plates as described (3, 7, 8). Cells were inoculated in a volume of 135  $\mu$ l at a density of 5000 cells/well. Fifteen  $\mu$ l of inhibitors diluted with medium were added, and the cells were cultured for 4 days. Control wells received vehicle alone. Fifteen  $\mu$ l of MTT solution (5 mg/ml in PBS) were added and further incubated for 4 h. The resulting MTT formazan was solubilized by addition of 100  $\mu$ l of SDS solution (20% in 10 mM HCl), and the absorbance was measured after 24 h at 570 nm and a reference wavelength of 690 nm using a microplate reader.

**DNA Fragmentation Assay.** Cells were seeded in polyHEMA-coated or uncoated tissue culture plastic 35-mm

dishes and incubated for 24 h. Cells were treated with inhibitors for 24–48 h, washed with PBS, and lysed with 10 mM Tris-HCl (pH 7.4), 10 mM EDTA, and 0.5% Triton X-100. The low molecular weight DNA-containing fraction was isolated by centrifugation at 10,000  $\times g$  for 10 min. Supernatants containing equal amounts of protein were treated with 20  $\mu$ g/ml RNase A for 1 h and then with 20  $\mu$ g/ml proteinase K for 30 min at 37°C. DNA was 2-propanol precipitated, run on a 2% agarose gel, and visualized by SYBR Green I staining.

**Immunoblotting Analysis.** Cells were seeded as above, treated with inhibitors for 6–24 h, washed with cold PBS, fixed for 10 min with 10% cold trichloroacetic acid, and lysed with 80  $\mu$ l of 9 M urea and 2% Triton X-100 and 20  $\mu$ l of 10% lithium dodecyl sulfate. Lysates were neutralized with 2 M Tris, sonicated to reduce viscosity and normalized for protein. Equal amounts of protein were electrophoresed through SDS-PAGE, immunoblotted, and detected by enhanced chemiluminescence.

## Results

### U0126 Inhibits Anchorage-independent Growth of Human Breast Cancer Cell Lines with Elevated ERK Activity.

We reported that the MEK inhibitor U0126 (9) selectively suppressed anchorage-independent growth of *Ki-ras*-transformed rat fibroblasts (3). To explore the potency of U0126 on human cancer cells of epithelial origin, we examined the inhibitor's effects on anchorage independence of human breast cancer cell lines. The cell lines displayed different responses to the inhibitor. Of the eight lines tested, the growth of MDA-MB231 and HBC4 was suppressed by U0126 on the nonadhesive polyHEMA-coated surface at concentrations lower than on plastic (Fig. 1). Other cell lines did not exhibit increased sensitivity to U0126 in polyHEMA-coated plates. Neither Adriamycin nor etoposide showed any selectivity between the two surfaces in any of the cells (data not shown).

To search for correlation between U0126 responsiveness and ERK activity, we examined the status of ERK phosphorylation/activation in the breast cancer cells by immunoblotting. As shown in Fig. 2, MDA-MB231 and HBC4, the two cell lines that showed increased sensitivity to U0126 when non-anchored, had higher levels of phosphorylated ERK than the other lines. Total ERK was similarly expressed in all cell lines. Hoshino *et al.* (10) reported that ERK is constitutively activated in MDA-MB231 and HBC4. These cells showed high ERK activity, even in the absence of growth factor stimulation.

**U0126 Sensitizes MDA-MB231 and HBC4 Cells to Anoikis.** Most normal cell types undergo apoptosis upon detachment from the matrix, a phenomenon referred to as anoikis. Evidently, tumor cells must acquire anoikis resistance to grow independently of anchorage. We explored the possibility that U0126 selectively inhibits anchorage-independent growth of MDA-MB231 and HBC4 cells by rendering these cells anoikis sensitive.

Exposure of MDA-MB231 and HBC4 cells to U0126 at 10  $\mu$ M for 24 h led to DNA nucleosomal fragmentation when cells were deprived of anchorage but not when attached (Fig. 3A). Furthermore, other features of apoptotic cell death

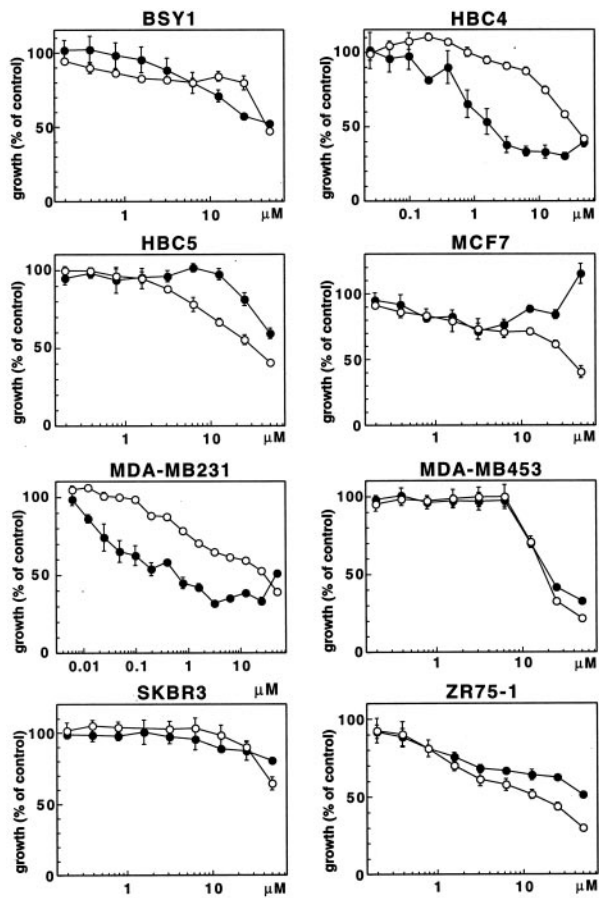


Fig. 1. Effect of U0126 on anchorage-independent (●) and anchorage-dependent growth (○) of human breast tumor cell lines. Cells were cultured in polyHEMA-coated (anchorage-independent growth) or uncoated (anchorage-dependent growth) tissue culture plastic 96-well plates and quantitated using the MTT assay as described in "Materials and Methods." Each plot represents means of quadruplicate wells; bars, SD.

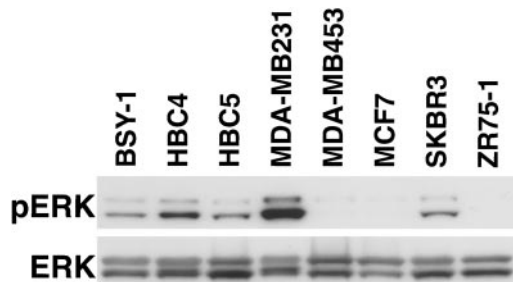


Fig. 2. Phosphorylation and protein levels of ERK in human breast tumor cell lines. Cell lysates were electrophoresed through 10% SDS-PAGE, followed by immunoblotting using anti-phospho-ERK or a mixture of anti-ERK1 and anti-ERK2 antibodies. pERK, phosphorylated ERK. Samples were prepared from anchored cells. Similar results were obtained with nonanchored cells (not shown).

(caspase 3 cleavage and morphology) were also observed, exclusively in nonanchored cells (Figs. 6 and 7). Nucleosomal DNA ladder was not observed in MDA-MB453 or SKBR3 (Fig. 3B) or in other cell lines (not shown), even at 50  $\mu$ M

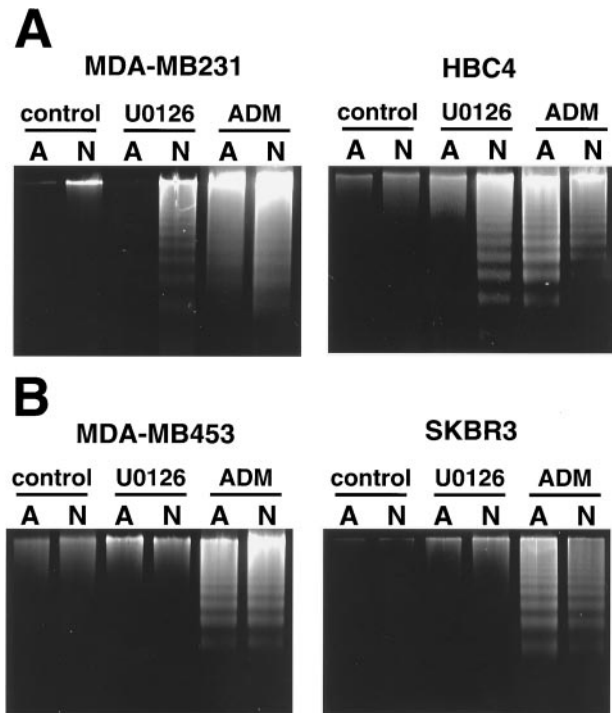


Fig. 3. Effects of U0126 and Adriamycin (ADM) on nucleosomal DNA fragmentation in anchored (A) and nonanchored (N) human breast tumor cell lines. A, U0126 induces nucleosomal DNA fragmentation in nonanchored but not in anchored MDA-MB231 and HBC4 cells. Cells were treated with U0126 (10  $\mu$ M) for 24 h or with Adriamycin (1  $\mu$ g/ml) for 24 h (HBC4) or 48 h (MDA-MB231). B, U0126 does not induce nucleosomal DNA fragmentation in MDA-MB453 and SKBR3 cells. Cells were treated with U0126 (50  $\mu$ M) or Adriamycin (1  $\mu$ g/ml) for 24 h. Cytosolic DNAs were analyzed by agarose gel electrophoresis as described in "Materials and Methods."

U0126. Adriamycin induced apoptosis, irrespective of anchorage in every cell line tested (Fig. 2 and not shown). The results indicate that U0126 induced anoikis sensitivity in human breast tumor cells with a constitutively activated ERK pathway, thereby selectively inhibiting anchorage-independent growth in polyHEMA-coated plates.

**PD98059 Renders MDA-MB231 Cells Anoikis Sensitive, But Induction of Anoikis Sensitivity in HBC4 Cells Requires Further Addition of Rapamycin.** We reported that simultaneous blockade of ERK and p70<sup>S6K</sup> pathways is necessary to reverse Ki-ras-mediated transformation in rat fibroblasts (3). U0126 inhibited both pathways and restored the normal phenotype. Another MEK inhibitor, PD98059 (11), only marginally influenced the p70<sup>S6K</sup> pathway and required addition of the mTOR-p70<sup>S6K</sup> pathway inhibitor rapamycin (12–15) to inhibit anchorage-independent growth of Ki-ras-transformed fibroblasts. Transformation by Ha-ras, on the other hand, appeared to be normalized by PD98059 alone.

We examined whether PD98059 by itself would inhibit anchorage-independent growth of human breast cancer cell lines. As shown in Fig. 4, PD98059 selectively inhibited anchorage-independent growth of MDA-MB231 cells. However, the compound did not inhibit anchorage-independent growth of HBC4 cells (Fig. 4) or other breast cancer cells (not



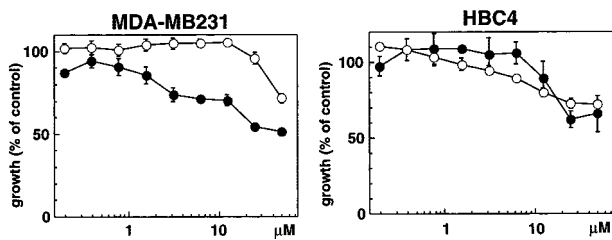


Fig. 4. Effect of PD98059 on anchorage-independent (●) and anchorage-dependent growth (○) of MDA-MB231 and HBC4 cells. Cells were cultured as in Fig. 1. Each plot represents means of quadruplicate wells; bars, SD.

shown). Consistent with the above results, PD98059 induced anoikis sensitivity in MDA-MB231 cells but not in HBC4 cells, as determined by nucleosomal DNA fragmentation, caspase 3 activation, and morphology (Figs. 5–7). These features of apoptosis were not observed in attached MDA-MB231 cells. We anticipated that the combination of PD98059 and rapamycin would mimic actions of U0126 and render HBC4 cells anoikis sensitive. As shown in Figs. 5–7, the combination of PD98059 and rapamycin sensitized HBC4 cells to apoptosis in suspension. Again, apoptotic features were detected only in nonanchored cells, and anchored cells remained viable. Rapamycin by itself did not activate any apoptotic response in MDA-MB231 or HBC4 cells, anchored or nonanchored, whereas Adriamycin induced apoptosis in both cell lines regardless of anchorage.

**Induction of Anoikis Sensitivity in MDA-MB231 and HBC4 Cells Requires Concurrent Inhibition of ERK and p70<sup>S6K</sup> Pathways.** The above results raised the possibility that inhibition of the ERK pathway alone is sufficient for anoikis execution in MDA-MB231 cells. Alternatively, the p70<sup>S6K</sup> pathway of MDA-MB231 cells might be more susceptible to PD98059 than that of HBC4 cells. To study the biochemical events that underlie induction of anoikis in MDA-MB231 and HBC4 cells, we examined the effects of the MEK inhibitors on activation of ERK and p70<sup>S6K</sup> pathways in anchored *versus* nonanchored cells by monitoring phosphorylation of ERK and S6 ribosomal protein. In contrast to ERK phosphorylation, all of the cell lines showed similar basal S6 ribosomal protein phosphorylation levels, which were not influenced by anchorage (not shown).

U0126 at 10  $\mu\text{M}$  for 6 h essentially abolished ERK phosphorylation in both MDA-MB231 and HBC4 cells, anchored or nonanchored (Fig. 8). U0126 also significantly reduced S6 ribosomal protein phosphorylation, although requiring somewhat longer treatment in HBC4 cells. On the other hand, PD98059 in anchored cells was more selective for the ERK pathway and only slightly reduced phospho-S6 ribosomal protein. Removal of anchorage appeared to sensitize the p70<sup>S6K</sup> pathway to PD98059 in both cell lines but with greater impact on MDA-MB231. Whereas S6 ribosomal protein in suspended MDA-MB231 cells underwent complete dephosphorylation, a noticeable level of phosphorylated form was still detected in HBC4 cells. Rapamycin selectively inhibited the mTOR pathway of both cell lines, with and without anchorage, and did not influence phosphorylation

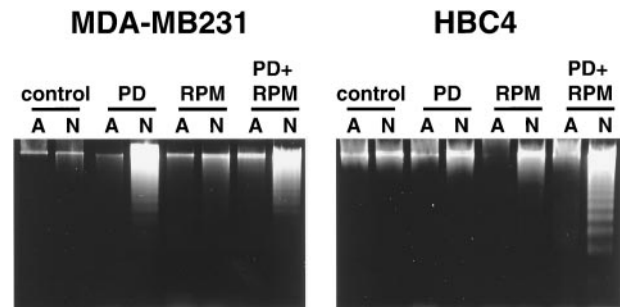


Fig. 5. Effects of PD98059 (PD), rapamycin (RPM), or PD98059 plus rapamycin (PD + RPM) on nucleosomal DNA fragmentation in anchored (A) or nonanchored (N) MDA-MB231 and HBC4 cells. Cells were cultured on tissue culture plastic or polyHEMA-coated plates in the absence or presence of inhibitors for 48 h. Concentrations used were: PD98059, 20  $\mu\text{M}$ ; rapamycin, 25 nM.

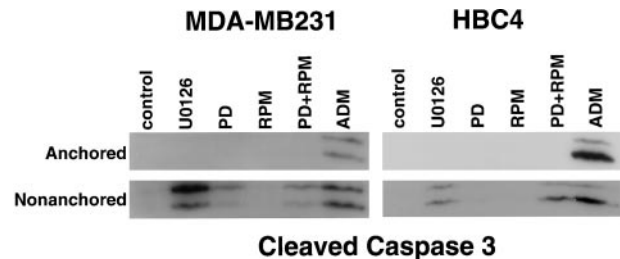
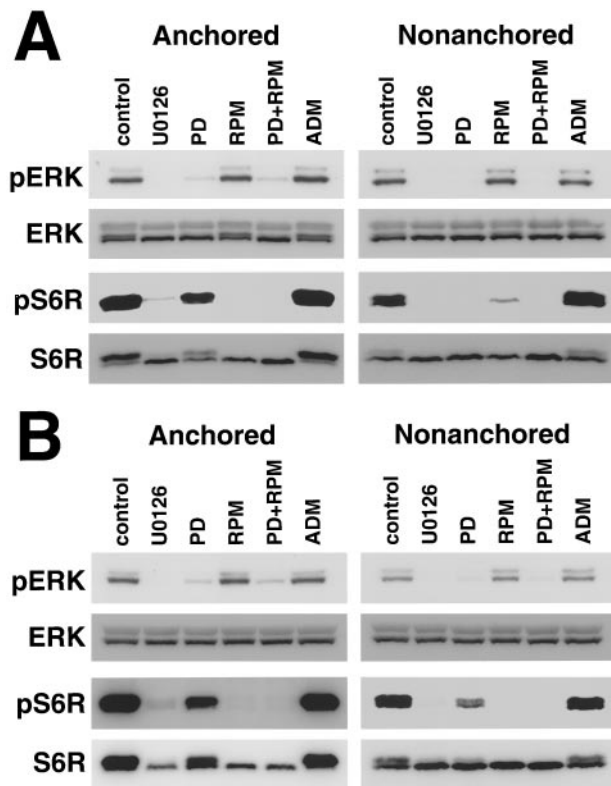


Fig. 6. Immunoblot analysis of caspase 3 cleavage in anchored or nonanchored MDA-MB231 and HBC4 cells treated with U0126, PD98059 (PD), rapamycin (RPM), PD98059 plus rapamycin (PD + RPM), or Adriamycin (ADM). Cells were cultured on tissue culture plastic or polyHEMA-coated plates in the absence or presence of inhibitors for 48 h. Cell lysates were electrophoresed through 15% SDS-PAGE, followed by immunoblotting using anti-cleaved caspase 3 antibody. Concentrations used were: U0126, 10  $\mu\text{M}$ ; PD98059, 20  $\mu\text{M}$ ; rapamycin, 25 nM; Adriamycin, 1  $\mu\text{g/ml}$ .

status of ERK. Combination of PD98059 and rapamycin inhibited both ERK and p70<sup>S6K</sup> activity in all cellular settings. Adriamycin had no effect on ERK or S6 ribosomal protein phosphorylation. Thus, MDA-MB231 and HBC4 cells underwent apoptosis in situations in which ERK and p70<sup>S6K</sup> pathways were both blocked and deprived of anchorage. Separate interference of these pathways had little effect on survival, and anchored cells remained viable even when both pathways appeared to be fully inhibited.

We also examined the effect of U0126 on the phosphorylation status of S6 ribosomal protein in MDA-MB453 and SKBR3 cells. As shown above, U0126 does not sensitize these cells to anoikis. S6 ribosomal protein phosphorylation of MDA-MB453 was completely insensitive to U0126, and that of SKBR3 was considerably refractory (Fig. 9). Rapamycin, however, still inhibited S6 ribosomal protein phosphorylation in these cells. The combination of U0126 and rapamycin blocked both ERK and p70<sup>S6K</sup> pathways but did not induce anoikis sensitivity in MDA-MB453 and SKBR3 (not shown). The results suggest that susceptibility of p70<sup>S6K</sup> to MEK inhibitors may be one of the determinants of anoikis sensitivity.





**Fig. 8.** Immunoblot analysis of phosphorylation level of ERK and S6 ribosomal protein in anchored or nonanchored MDA-MB231 (A) and HBC4 (B) cells treated with inhibitors. MDA-MB231 cells were treated for 6 h. HBC4 cells were treated for 6 h (for ERK analysis) or 15 h (for S6 ribosomal protein analysis). Concentrations used were; U0126, 10  $\mu$ M; PD98059, 20  $\mu$ M; rapamycin, 25 nM; Adriamycin, 1  $\mu$ g/ml. Cell lysates were electrophoresed through 10% SDS-PAGE, followed by immunoblotting using phospho-ERK or phospho-S6 ribosomal protein-specific antibodies. Filters were stripped and reprobed with antibodies against total ERK or S6 ribosomal protein. PD, PD98059; RPM, rapamycin; ADM, Adriamycin; pERK, phosphorylated ERK; pS6R, phosphorylated S6 ribosomal protein.

It is unclear how p70<sup>S6K</sup> is inhibited. We examined the effects of the recently introduced MEK inhibitor PD184352 (17) on anchorage independence of human tumor cell lines. This compound proved to be effective in inhibiting anchorage-independent growth of HBC4 cells and also inhibited the p70<sup>S6K</sup> pathway in this cell line.<sup>4</sup> U0126, PD98059, and PD184352 are structurally dissimilar, and the p70<sup>S6K</sup> pathway blockade by these compounds is conceivably a consequence of MEK inhibition. Compared with PD98059, U0126 has considerably higher affinity to all forms of MEK (9). Although both compounds appeared to significantly suppress ERK, a subtle difference in the level of residual activity probably accounts for the greater impact of U0126 on p70<sup>S6K</sup> in a wider range of cells. On the basis of the inability of PD98059 to suppress p70<sup>S6K</sup> in many cells, we speculate that inhibition of the p70<sup>S6K</sup> pathway by MEK inhibitors requires absolute or near complete shutoff of ERK signals.

<sup>4</sup> H. Fukazawa and Y. Uehara, unpublished observation.



**Fig. 9.** Immunoblot analysis of phosphorylation level of S6 ribosomal protein in anchored or nonanchored MDA-MB453 and SKBR3 cells treated for 24 h with U0126 (U) or rapamycin (R). Concentrations used were: U0126, 10  $\mu$ M; rapamycin, 25 nM. Cell lysates were electrophoresed through 10% SDS-PAGE followed by immunoblotting using anti phospho-S6 ribosomal protein antibody. pS6R, phosphorylated S6 ribosomal protein; C, vehicle control.

Inhibitors of the p70<sup>S6K</sup> pathway may synergize to block malignant growth when total ERK inhibition is not attainable.

In general, p70<sup>S6K</sup> has been considered to be controlled through a mechanism that is dependent on PI3K and AKT but independent of ERK (18–21). However, recent reports demonstrate that MEK inhibitors can suppress p70<sup>S6K</sup> in several cellular settings. Effects of MEK inhibitors and PI3K inhibitors on p70<sup>S6K</sup> vary in different systems and also depend on activating stimuli. For example, in human embryonic kidney 293 cells, activation of p70<sup>S6K</sup> by phorbol ester was sensitive to PD98059 and U0126 but insensitive to the PI3K inhibitor wortmannin (22). By contrast, in the same cells, activation by insulin was sensitive to wortmannin but insensitive to MEK inhibitors. p70<sup>S6K</sup> activation by nitric oxide in rat adventitial fibroblasts and by angiotensin II in rat vascular smooth muscle cells was sensitive to both MEK and PI3K inhibitors (23). Thus, there appears to be at least two pathways that regulate p70<sup>S6K</sup> activity, one that requires PI3K and another that depends on the MEK-ERK module. These two systems may function simultaneously within a cell and may cross-talk at various levels to influence each other, generating further complexity in mechanisms of p70<sup>S6K</sup> control. Our data indicate that diverse modes of p70<sup>S6K</sup> control exist in human cancers, and that in some cases ERK is the major upstream regulator.

As shown in Fig. 1, there were distinct differences in response to U0126 among the human breast cancer cell lines. Susceptibility to conventional antitumor agents such as Adriamycin and etoposide was not as diverse. They suppressed both anchorage-dependent and -independent growth of all of the cell lines assessed at comparable concentrations. These *in vitro* results can be extrapolated to various effects of MEK inhibitors in clinical situations. Tumors that rely heavily on ERK for growth and survival are expected to be extremely susceptible to MEK inhibitors, whereas some tumors may be totally unresponsive. Prognosis of sensitivity from biochemical and genetic profiles will be of particular importance in clinical application of MEK inhibitors.

However, oncogenic growth involves irregularity of several pathways, and reciprocal interdependence and cross-talk of multiple pathways would add further complication in predicting consequences of MEK-ERK intervention. To gain insight into determinants of susceptibility to MEK inhibitors, we have extended our study to a large panel of human cancer cell lines. MEK inhibitors proved to be effective in suppressing anchorage-independent growth of several other cancer cell



lines, notably of colon. Although preliminary results suggested that tumors vulnerable to MEK inhibitors generally have elevated ERK, the correlation was not perfect, and some tumors with high levels of phosphorylated ERK were completely refractory. It is likely that tumors acquire anoikis resistance through various mechanisms, and even tumors with constitutively activated ERK may depend primarily on other pathways to evade anoikis. We anticipate that MEK inhibitors will still be useful in treatment of such tumors in combination with other targeted therapies and are currently testing formulas containing MEK inhibitors and other signal transduction inhibitors.

In summary, we provide data that MEK inhibitors induce anoikis sensitivity in human breast cancer cell lines with high levels of activated ERK. Preclinical assessment of targeted therapies has been suggested to require nontraditional approaches. Our results indicate that a simple growth inhibition assay on solid support may underestimate the efficacy of MEK inhibitors. We propose incorporation of anoikis assays in assessment of agents that target signaling molecules to help prevent overlooking unexpected activities.

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### References

- Macpherson, I., and Montagnier, L. Agar suspension culture for the selective assay of cells transformed by polyoma virus. *Virology*, 23: 291–294, 1964.
- Shin, S., Freedman, V. H., Risser, R., and Pollack, R. Tumorigenicity of virus-transformed cells in nude mice is correlated specifically with anchorage independent growth *in vitro*. *Proc. Natl. Acad. Sci. USA*, 72: 4435–4439, 1975.
- Fukazawa, H., and Uehara, Y. U0126 reverses Ki-ras-mediated transformation by blocking both mitogen-activated protein kinase and p70 S6 kinase pathways. *Cancer Res.*, 60: 2104–2107, 2000.
- Meredith, J. E., Fazeli, B., and Schwartz, M. A. The extracellular matrix as a cell survival factor. *Mol. Biol. Cell*, 4: 953–961, 1993.
- Frisch, S. M., and Francis, H. Disruption of epithelial cell-matrix interactions induces apoptosis. *J. Cell Biol.*, 124: 619–626, 1994.
- Meredith, J. E., and Schwartz, M. A. Integrins, adhesion and apoptosis. *Trends Cell Biol.*, 7: 146–150, 1997.
- Fukazawa, H., Mizuno, S., and Uehara, Y. A microplate assay for quantitation of anchorage-independent growth of transformed cells. *Anal. Biochem.*, 228: 83–90, 1995.
- Kawada, M., Uehara, Y., Mizuno, S., Yamori, T., and Tsuruo, T. Up-regulation of p27Kip1 correlates inversely with anchorage-independent growth of human cancer cell lines. *Jpn. J. Cancer Res.*, 89: 110–115, 1998.
- Favata, M. F., Horiuchi, K. Y., Manos, E. J., Daulerio, A. J., Stradley, D. A., Feese, W. S., Van Dyk, D. E., Pitts, W. J., Earl, R. A., Hobbs, F., Copeland, R. A., Magolda, R. L., Scherle, P. A., and Trzaskos, J. M. Identification of a novel inhibitor of mitogen-activated protein kinase kinase. *J. Biol. Chem.*, 273: 18623–18632, 1998.
- Hoshino, R., Chatani, Y., Yamori, T., Tsuruo, T., Oka, H., Yoshida, O., Shimada, Y., Ari-i, S., Wada, H., Fujimoto, J., and Kohno, M. Constitutive activation of the 41-/43-kDa mitogen-activated protein kinase signaling pathway in human tumors. *Oncogene*, 18: 813–822, 1999.
- Alessi, D. R., Cuenda, A., Cohen, P., Dudley, D. T., and Saltiel, A. R. PD 098059 is a specific inhibitor of the activation of mitogen-activated protein kinase kinase *in vitro* and *in vivo*. *J. Biol. Chem.*, 270: 27489–27494, 1995.
- Kuo, C. J., Chung, J., Fiorentino, D. F., Flanagan, W. M., Blenis, J., and Crabtree, G. R. Rapamycin selectively inhibits interleukin-2 activation of p70 S6 kinase. *Nature (Lond.)*, 358: 70–73, 1992.
- Price, D. J., Grove, J. R., Calvo, V., Avruch, J., and Bierer, B. E. Rapamycin-induced inhibition of the 70-kilodalton S6 protein kinase. *Science (Wash. DC)*, 257: 973–977, 1992.
- Brown, E. J., Beal, P. A., Keith, C. T., Chen, J., Shin, T. B., and Schreiber, S. L. Control of p70 s6 kinase by kinase activity of FRAP *in vivo*. *Nature (Lond.)*, 377: 441–446, 1995.
- Sabers, C. J., Martin, M. M., Brunn, G. J., Williams, J. M., Dumont, F. J., Wiederrecht, G., and Abraham, R. T. Isolation of a protein target of the FKBP12-rapamycin complex in mammalian cells. *J. Biol. Chem.*, 270: 815–822, 1995.
- Ruoslahti, E. Fibronectin and its integrin receptors in cancer. *Adv. Cancer Res.*, 76: 1–20, 1999.
- Sebolt-Leopold, J. S., Dudley, D. T., Herrera, R., Van Becelaere, K., Wiland, A., Gowan, R. C., Tecle, H., Barrett, S. D., Bridges, A., Przybranowski, S., Leopold, W. R., and Saltiel, A. R. Blockade of the MAP kinase pathway suppresses growth of colon tumors *in vivo*. *Nat. Med.*, 5: 810–816, 1999.
- Chung, J., Grammer, T. C., Lemon, K. P., Kazlauskas, A., and Blenis, J. PDGF- and insulin-dependent pp70S6k activation mediated by phosphatidylinositol-3-OH kinase. *Nature (Lond.)*, 370: 71–75, 1994.
- Ming, X. F., Burgering, B. M., Wennstrom, S., Claesson-Welsh, L., Heldin, C. H., Bos, J. L., Kozma, S. C., and Thomas, G. Activation of p70/p85 S6 kinase by a pathway independent of p21ras. *Nature (Lond.)*, 371: 426–429, 1994.
- Weng, Q. P., Andrabi, K., Klippel, A., Kozlowski, M. T., Williams, L. T., and Avruch, J. Phosphatidylinositol 3-kinase signals activation of p70 S6 kinase *in situ* through site-specific p70 phosphorylation. *Proc. Natl. Acad. Sci. USA*, 92: 5744–5748, 1995.
- von Manteuffel, S. R., Gingras, A. C., Ming, X. F., Sonenberg, N., and Thomas, G. 4E-BP1 phosphorylation is mediated by the FRAP-p70s6k pathway and is independent of mitogen-activated protein kinase. *Proc. Natl. Acad. Sci. USA*, 93: 4076–4080, 1996.
- Herbert, T. P., Kilhams, G. R., Batty, I. H., and Proud, C. G. Distinct signalling pathways mediate insulin and phorbol ester-stimulated eukaryotic initiation factor 4F assembly and protein synthesis in HEK 293 cells. *J. Biol. Chem.*, 275: 11249–11256, 2000.
- Gu, M., Lynch, J., and Brecher, P. Nitric oxide increases p21(Waf1/Cip1) expression by a cGMP-dependent pathway that includes activation of extracellular signal-regulated kinase and p70(S6k). *J. Biol. Chem.*, 275: 11389–11396, 2000.