Identification of Common Predictive Markers of In vitro Response to the Mek Inhibitor Selumetinib (AZD6244; ARRY-142886) in Human Breast Cancer and Non–Small Cell Lung Cancer Cell Lines

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Abstract
Selumetinib (AZD6244; ARRY-142886) is a tight-binding, uncompetitive inhibitor of mitogen-activated protein kinase kinases (MEK) 1 and 2 currently in clinical development. We evaluated the effects of selumetinib in 31 human breast cancer cell lines and 43 human non–small cell lung cancer (NSCLC) cell lines to identify characteristics correlating with in vitro sensitivity to MEK inhibition. IC50 <1 μmol/L (considered sensitive) was seen in 5 of 31 breast cancer cell lines and 15 of 43 NSCLC cell lines, with a correlation between sensitivity and raf mutations in breast cancer cell lines (P = 0.022) and ras mutations in NSCLC cell lines (P = 0.045). Evaluation of 27 of the NSCLC cell lines with Western blots showed no clear association between MEK and phosphoinositide 3-kinase pathway activation and sensitivity to MEK inhibition. Baseline gene expression profiles were generated for each cell line using Agilent gene expression arrays to identify additional predictive markers. Genes associated with differential sensitivity to selumetinib were seen in both histologies, including a small number of genes in which differential expression was common to both histologies. In total, these results suggest that clinical trials of selumetinib in breast cancer and NSCLC might select patients whose tumors harbor raf and ras mutations, respectively. Mol Cancer Ther; 9(7); 1985–94. ©2010 AACR.

Introduction
The ras/raf/mitogen-activated protein kinase kinase (MEK)/extracellular signal-regulated kinase (ERK) pathway is activated in many solid tumors (1). A variety of events can induce ras into its GTP bound, active state. ras recruits raf, a serine/threonine kinase that in turn phosphorlyates MEK 1 and 2. MEK1/2 are threonine/tyrosine protein kinases, and their only known phosphorlyation targets are ERK 1 and 2. ERK1/2 phosphorylate several nuclear proteins, resulting in proliferation and migration (2). This pathway is felt to be important in many malignancies, including non–small cell lung cancer (NSCLC) and breast cancer. In NSCLC, this pathway is activated by ras mutations in 20% to 30% of cases (3). Mutations in ras are associated with poor prognosis (4) and resistance to epidermal growth factor receptor (EGFR) inhibitors (5, 6). Mutations in ras and raf are less common in breast cancer, with an incidence of 4% and 7%, respectively (7).

Laboratory data indicate that mutations in ras or raf (8, 9) in NSCLC and breast cancer, specifically the non–luminal subtype (10), are associated with response to MEK inhibition. Given the specific and potent inhibition of MEK with available pharmacologic agents, most laboratory-based publications have relied on MEK inhibition. Other methods such as inhibition via small interfering RNA (siRNA), have yielded results similar to those seen with pharmacologic MEK inhibition (11). The phosphoinositide 3-kinase (PI3K)/AKT/mTOR pathway is an important alternative downstream pathway that has been hypothesized to provide an escape mechanism for some cell lines to MEK inhibition (12). PI3K pathway activation (via PI3KCA mutation) has been shown to predict resistance to MEK inhibition in ras mutants (13). In vivo and in vitro models showed that the combined inhibition of MEK and PI3K pathways increased apoptosis in lines resistant to MEK inhibition alone, particularly in cell lines with both ras
and PI3K pathway mutations. In vivo combination of a PI3K/mTOR inhibitor and a MEK inhibition in ras mutant tumors showed synergy (14).

The first MEK inhibitor to enter clinical trials was CI-1040, an oral small molecule inhibiting MEK1/2 (15). In a phase I clinical trial enrolling 66 patients, 1 partial response was seen in a patient with pancreatic cancer, and 19 patients experienced stable disease (16). These encouraging results were evaluated in a phase II study of unselected patients with NSCLC, breast cancer, colon cancer, and pancreatic cancer. The results were less robust, with no objective responses in 67 patients, and stable disease in only 8 patients (17).

Selumetinib (AZD6244; ARRY-142886) is a second-generation MEK inhibitor currently in clinical development. It is a potent, tight-binding, uncompetitive MEK inhibitor with an IC50 of 14 nmol/L against purified MEK1 (18). To test the hypothesis that a subgroup of human breast cancer cell lines and NSCLC cell lines would be more sensitive to MEK inhibition by selumetinib, we carried out a series of preclinical studies in large panels of molecularly characterized human cell lines from both histologies.

Materials and Methods

Cell lines, cell cultures, and reagents

Selumetinib was studied in 31 human breast cancer cell lines and 43 human NSCLC cell lines in vitro (see Supplement). MDA-MB-134, MDA-MB-415, MDA-MB-436, MDA-MB-175, UACC-893, UACC-812, and MDA-MB-157 cell lines were cultured in L15 medium [American Type Culture Collection (ATCC)] supplemented with 10% heat-inactivated fetal bovine serum (FBS; Omega Scientific), 2 mmol/L glutamine (Invitrogen), and 1% penicillin G-streptomycin-fungizone solution (PSF; Irvine Scientific). CAL-51, KPL-1, and HS578T cells were grown in DMEM (Cellgro) supplemented with 10% heat-inactivated FBS (FBS; Omega Scientific), 2 mmol/L glutamine (Invitrogen), and 1% penicillin G-streptomycin-fungizone solution (PSF; Irvine Scientific). CAL-51, KPL-1, and HS578T cells were grown in DMEM (Cellgro) supplemented with 10% heat-inactivated FBS (FBS; Omega Scientific), 2 mmol/L glutamine (Invitrogen), and 1% penicillin G-streptomycin-fungizone solution (PSF; Irvine Scientific). CAL-51, KPL-1, and HS578T cells were grown in DMEM (Cellgro) supplemented with 10% heat-inactivated FBS (FBS; Omega Scientific), 2 mmol/L glutamine (Invitrogen), and 1% penicillin G-streptomycin-fungizone solution (PSF; Irvine Scientific). CAL-51, KPL-1, and HS578T cells were grown in DMEM (Cellgro) supplemented with 10% heat-inactivated FBS (FBS; Omega Scientific), 2 mmol/L glutamine (Invitrogen), and 1% penicillin G-streptomycin-fungizone solution (PSF; Irvine Scientific). CAL-51, KPL-1, and HS578T cells were grown in DMEM (Cellgro) supplemented with 10% heat-inactivated FBS (FBS; Omega Scientific), 2 mmol/L glutamine (Invitrogen), and 1% penicillin G-streptomycin-fungizone solution (PSF; Irvine Scientific). CAL-51, KPL-1, and HS578T cells were grown in DMEM (Cellgro) supplemented with 10% heat-inactivated FBS (FBS; Omega Scientific), 2 mmol/L glutamine (Invitrogen), and 1% penicillin G-streptomycin-fungizone solution (PSF; Irvine Scientific).

Microarray analysis of cell lines

Agilent microarray analyses were done to assess baseline gene expression for each cell line. The techniques used have been described in detail elsewhere (19, 20). Briefly, cells were grown to log phase. RNA was extracted using the RNeasy Kit (Qiagen). Purified RNA was eluted in 30 to 60 μL diethyl pyrocarbonate water, and the quantity of RNA was measured by spectral analysis using the Nanodrop Spectrophotometer (Thermo Fisher Scientific). RNA separation via capillary electrophoresis using the Agilent 2000 Bioanalyzer was done to determine RNA quality. Microarrays of breast cancer cell lines and NSCLC cell lines were then carried out on Agilent Human 1A V1 chips and V2 chips, respectively. Individual cell lines were characterized by comparison with a histology-specific mixed reference pool on a single slide in which the mixed pool RNA was labeled with cyanine-3 and the individual cell lines with cyanine-5. The breast cancer mixed reference pool consisted of equal amounts of RNA from 10 breast cancer cell lines (see Supplement) selected to be representative of a range of the various known breast cancer subtypes based on their expression of specific molecular markers, e.g., ESR1, human epidermal growth factor receptor 2 (HER2), epidermal growth factor receptor (EGFR), as well as growth characteristics. The NSCLC mixed reference pool consisted of equal amounts of RNA from 45 NSCLC cell lines (see Supplement).

Microarray slides were read using an Agilent Scanner, and Agilent Feature Extraction software version 7.5 was used to calculate gene expression values. The feature extracted files were imported into the Rosetta Resolver system version 7.1 for gene expression data analysis (Rosetta Biosoftware). The intensity ratios between the cell line sample and mixed reference were calculated for each sequence and were computed according to the Agilent error model. A particular sequence was considered differentially expressed if the calculated P value of change was ≤0.01.

Proliferation assays

Cells were plated in 24-well plates at a density of 5 × 104 to 1 × 105 cells per well and grown in cell line-specific medium with decreasing concentrations of selumetinib from 10 μmol/L to 1 nmol/L. These data were compared with untreated controls. Cells were harvested by trypsinization on day 6 and counted immediately using a Coulter Z2 particle counter (Beckman Coulter Inc.). Percent inhibition was calculated as 1 - (cell count divided by cell count of untreated controls). Experiments were done in duplicate. IC50 was calculated using a linear regression curve fit (Calcusyn, Biosoft).
Cell cycle analysis
The effects of selumetinib on cell cycle were assessed using Nim-4', 6-diamidino-2-phenylindole (DAPI) staining. Cells were plated evenly in control and experimental wells and allowed to grow to log-phase then treated with 1 μmol/L selumetinib for 48 hours. Cells were washed with PBS, and trypsin was applied. Cells were then centrifuged at 3,000 rpm for 5 minutes. Supernatant was aspirated and cells were resuspended in 100 μL of Nim-DAPI (NPE Systems) and gently vortexed. Cells were analyzed with UV using a Cell Lab Quanta SC flow cytometer (Beckman-Coulter).

Statistical methods
Fisher’s exact test was used to determine potential relationships between mutational status and selumetinib response. Mutational status was evaluated using publicly available data at the Sanger website (7). Human breast cancer cell lines were profiled on the Agilent Human 1A V1 platform that contains 17,086 probes including known genes and expressed sequence tags. Human NSCLC cell lines were profiled on the Agilent Human 1A V2 chip, which covers 18,716 probes. The Resolver system ANOVA and hierarchical cluster analysis of the cell line expression profiles were used to compare the sensitive (IC₅₀ <1 μmol/L, excluding cell lines with SE inclusive of 1 μmol/L) and resistant (IC₅₀ >1 μmol/L, including cell lines with SE inclusive of 1 μmol/L). All ANOVAs were done with and without using the Benjamini-Hochberg false discovery rate multiple test correction, specifying a statistical cutoff for sequences of a 2-fold change in at least three experiments. The criterion used to determine differentially expressed genes was a P value <0.05. Sequence sets were compared using the Venn Diagram tool in the Resolver system. The two-dimensional cluster analysis was carried out using an agglomerative hierarchical clustering algorithm based on the cosine correlation similarity metric.

Western blots
Cells (see Supplement) growing in log-phase were exposed to media with or without 1 μmol/L selumetinib for 30 minutes prior to cell lysis. Cells were washed in ice-cold PBS and lysed at 4°C in lysis buffer. Insoluble material was cleared by centrifugation at 10,000 g for 10 minutes. Protein was quantitated using bicinchoninic acid (Pierce Biochemicals), resolved by SDS-PAGE, and transferred to nitrocellulose membranes (Invitrogen). Western blots were done to assess total ERK, phosphorylated ERK, total AKT, and phosphorylated AKT (at serine 308 and 473) among a subset of 27 of the lung cancer cell lines. Expression of phosphorylated AKT at serine 308 and 473 was detected by the monoclonal antibodies phospho AKT (Ser 308) and phospho AKT (Ser 473), respectively (Cell Signaling). Tubulin expression was detected by a-tubulin antibody 2144 (Cell Signaling).

Results
Sensitivity to selumetinib is correlated with raf mutations in human breast cancer cell lines and ras mutations in human NSCLC cell lines
Sensitivity to selumetinib was investigated in 31 human breast cancer cell lines (Fig. 1A). Five cell lines were sensitive to selumetinib, of which three had known BRAF mutations. None of the 26 resistant cell lines had a mutation in BRAF. Only one cell line had a KRAS mutation, and that cell line also had a mutation in BRAF and was sensitive. One cell line had a HRAS mutation, and that cell line had an IC₅₀ <1 μmol/L, but the SE included 1 μmol/L, and it was therefore not considered as part of the sensitive group. Mutations of genes other than raf were not clearly associated with response. In addition, 4 of 5 sensitive cell lines were HER2 amplified, whereas 10 of 26 resistant cell lines were HER2 amplified (P = 0.15; Table 1).

Sensitivity to selumetinib was investigated in 43 NSCLC cell lines (Fig. 1B). Fifteen cell lines were sensitive to selumetinib. Of the 15 sensitive cell lines, 9 (60%) had mutations in KRAS (8) or NRAS (1). In contrast, only 7 of the 28 (25%) resistant cell lines had ras mutations (P = 0.045). Sensitivity did not seem to correlate with any specific ras mutation (data not shown). Two of the lung cancer cell lines harbored raf mutations. Neither of these cell lines harbored the V600E mutation, and neither was among the sensitive cell lines. Mutations of genes besides ras and raf were not clearly associated with response.

Effects of selumetinib on cell cycle
To evaluate the effects of selumetinib on the cell cycle and to correlate these results with the antiproliferative effects of the compound we treated cell lines (see Supplement) with selumetinib at 1 μmol/L for 48 hours and then did flow cytometry using Nim-DAPI staining. Clear and pronounced G₀-G₁ arrest was seen in sensitive cell lines (Fig. 2A), but not in resistant cell lines (Fig. 2B).

Western blot of NSCLC cell lines in response to selumetinib
To assess the biochemical effect of selumetinib, Western blots were done to assess total ERK, phosphorylated ERK, total AKT, and phosphorylated AKT (at serine 308 and 473) among a subset of 27 of the lung cancer cell lines. All 16 ras mutant cell lines were evaluated (Fig. 3). In addition 11 ras wild-type cell lines were evaluated (Fig. 4). All 15 sensitive cell lines were evaluated
Twelve resistant cell lines were evaluated, including all of the cell lines with known ras mutations: H-23, H-460, H-647, H-2030, H-1734, H-1155, SHP-77 (Fig. 3B); PI3KCA mutations: H460, H1975; loss of PTEN: H1155; and raf mutations: H1666, H1755, in addition to lines without known mutations in these genes: H810, H2342 (Fig. 4B). Cell lines were evaluated at baseline, and after 30 minutes of treatment with 1 μmol/L of selumetinib. ERK phosphorylation was nearly eliminated in response to 1 μmol/L of selumetinib in all of the cell lines.
evaluated, regardless of sensitivity or mutational status. There was no change in AKT phosphorylation (308 or 473) in response to 1 \(\mu\)mol/L of selumetinib. There was a suggestion of higher baseline expression of pERK in cell lines with sensitivity to selumetinib. Overall, there was not a clear relationship between pAKT (serine 308 or 473) expression and response to growth inhibition with selumetinib. Cell lines with \(\text{PI3KCA}\) mutations (H460, H596, H-1975) and loss of \(\text{PTEN}\) (H1155) had high baseline expression of pAKT, and three of these cell lines were resistant.

**Identification of genes predictive of response to selumetinib in cell line panels**

In the breast cancer panel, gene expression data were available for all 31 cell lines. A total of 5,481 genes showed a 2-fold difference in expression in at least three experiments. ANOVA analysis showed 206 genes with a \(P\) value <0.05 between sensitive (\(n=5\)) and resistant (\(n=26\)) cell lines (Fig. 5A). Multiple test corrections algorithm showed only one gene, \(\text{PIK3R3}\), which was expressed at higher levels in resistant cell lines (Fig. 5B). \(\text{PIK3R3}\) binds IGF1R and INSR \textit{in vitro}, and is proposed to provide an alternative pathway to PI3K activation (21).

In the NSCLC cancer panel, gene expression data were available for 42 of the 43 cell lines evaluated. Fourteen were sensitive and 28 were resistant. A total of 7,662 genes showed a 2-fold difference in expression in at least three experiments. ANOVA analysis showed 337 differentially expressed genes with a \(P\) value <0.05 between sensitive and resistant cell lines (Fig. 5C).

### Table 1. Correlations between ras and raf mutations, breast cancer subtype, ER and HER2 status

<table>
<thead>
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<th></th>
<th>Sensitive</th>
<th>Resistant</th>
<th>(P^*)</th>
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<td></td>
<td></td>
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<td>7</td>
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<tr>
<td></td>
<td>ras wild-type</td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td>raf mutant</td>
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<td>0</td>
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<tr>
<td></td>
<td>HER2 normal</td>
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<td>16</td>
</tr>
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</table>

Abbreviation: ER, estrogen receptor.
*Computed using Fisher’s exact test.
Computing the ANOVA using a multiple test correction algorithm resulted in no differentially expressed genes. The average PIK3R3 expression was higher in resistant cell lines, but the observed variance between the sensitive and resistant groups did not reach statistical significance ($P = 0.13$).

Five genes were identified as being differentially expressed in both the breast cancer and the lung cancer panels: ABHD6, FAM77C, THC1981357, MMP7, and MSRA. ABHD6 was expressed at higher levels in sensitive cell lines in breast cancer and resistant cell lines in NSCLC. MMP7, a matrix metalloproteinase, was expressed at higher levels in resistant cell lines in breast cancer and sensitive cell lines in NSCLC. MSRA was increased in sensitive lines in both histologies. FAM77C and THC1981357 were decreased in sensitive lines in both histologies.

Discussion

Anticancer agents have generally been tested in an empirical fashion without regard to the molecular heterogeneity in a given histology. In many solid malignancies, therapeutic agents have been evaluated in patients that are most likely to benefit. Examples include antiestrogen therapy in tumors that express hormone receptors (22) or HER2-directed therapy in patients with amplification of HER2 (23, 24). Potentially active therapeutics may have failed to show benefit based on failure to determine those patients most likely to benefit, rather than absence of activity. With improvement in technology, the tools to preselect patients for therapeutic agents have become much more readily available.

We have shown a correlation between sensitivity to selumetinib and mutation in \( \text{ras} \) in human NSCLC cell lines and \( \text{raf} \) in human breast cancer cell lines. The differential effect of selumetinib could have been anticipated based on the role of MEK as a downstream kinase, propagating the signal of mutant \( \text{ras} \) or \( \text{raf} \). The low incidence of \( \text{ras} \) mutations in our human breast cancer cell lines and \( \text{raf} \) mutations (particularly V600E) in our human NSCLC cell lines limits our ability to assess those potential correlations. Only two of the breast cancer cell lines harbor mutations in \( \text{ras} \). MDA-MB-231, a cell line with a rare genotype in which mutations are present in both \( \text{BRAF} \) and \( \text{KRAS} \), is sensitive to selumetinib. HS578T, which harbors a mutation in \( \text{HRAS} \), has an IC\(_{50} < 1 \mu \text{mol/L} \), but the SE excludes 1\( \mu \text{mol/L} \), so it was not considered sensitive. Similarly, there were only two NSCLC cell lines that harbored a mutation in \( \text{raf} \), and neither was
sensitive. However, neither of these cell lines harbored the V600E mutation. H-1666 harbors a G466V and H-1755 harbors a G469A mutation. Non-V600E BRAF mutations have been shown to have lower kinase activity and may not be as important in the cancer phenotype as the V600E mutation (25). In addition, MEK inhibition in cell lines with non-V600E RAF mutations causes an increase in p-MEK via a feedback loop, which may diminish the efficacy of the drug to limit cell growth (26). Not all of the ras mutants in our NSCLC cell line panel were sensitive to MEK inhibition, which is consistent with past publications (13, 27–29). In the NSCLC cell line panel, there was no correlation between a specific ras mutation and sensitivity, although the number for each individual mutation was small and all are considered activating mutations. Our NSCLC panel included only three cell lines with EGFR mutations, and the results were mixed, making the role of selumetinib unclear in EGFR mutant tumors, although it would be anticipated that few such tumors would also harbor a mutation in ras.

In our panel, several of the lines resistant to MEK inhibition are known to harbor PI3KCA mutations (H-460, H-1975) or loss of PTEN (H-1155). However, one cell line with a PI3KCA mutation (H-596) was sensitive. Our study did not confirm a clear relationship between nonmutational PI3K pathway activation (as determined by pAKT expression) and response to MEK inhibition in ras mutants. Our NSCLC panel was larger than the panels tested in this fashion to date. Our data suggested a possible relationship between baseline pERK expression, and sensitivity, although the correlation was not entirely convincing.

The strongest link between sensitivity to MEK inhibition and the PI3K pathway in our work was seen in our baseline gene expression data. The only gene showing differential baseline expression in sensitive cell lines when a multiple test corrections algorithm was applied was PIK3R3 in the breast cancer panel. PIK3R3 is a regulatory subunit of PI3K. PIK3R3 was originally identified in a screen of proteins that bind the intracellular domain of IGF1R (21). PIK3R3 binds both IGF1R and INSR in vitro, and investigators have concluded that this interaction provides an alternative pathway to PI3K activation (21). PIK3R3 mRNA expression is significantly upregulated in ovarian cancer tissue as compared with normal ovarian tissue controls (30), and knockdown of PIK3R3 via siRNA resulted in significant apoptosis in ovarian cancer cell lines in vitro. In the current study, cell lines in which baseline expression of this gene was elevated were more resistant to selumetinib in both the breast and the NSCLC panels, although in the latter, statistical significance was not achieved ($P = 0.13$). Despite the lack of statistical significance in the NSCLC panel, this finding is intriguing and merits further study.

In any in vitro model of sensitivity, a distinction between sensitive and insensitive cell lines must be
made. The relevance of such a cutoff to clinical efficacy is always difficult to determine. In addition, although there were many cell lines that were clearly resistant to selumetinib (IC_{50} > 10 \mu \text{mol}/L), IC_{50} values were distributed along a continuum, rather than having an obvious break point between sensitive and resistant cell lines. We chose to limit sensitive cell lines to those that had an IC_{50} (± SE) < 1 \mu \text{mol}/L, based on this concentration being considered clinically achievable for this compound.

Recent data have shown that an activating mutation in MEKI is present in approximately 1% of primary lung cancer samples. NCI-H1437 harbors this mutation (31) and is sensitive to selumetinib. Further work will need to evaluate whether this mutation exists in other cell lines in our panel.

Although there were genes differentially expressed between sensitive and resistant cell lines in both panels, the relevance of these is unclear. Two of the genes, ABHD6 and MMP7, were upregulated in sensitive
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cell lines of one histology and downregulated in sensitive cell lines of the other histology, indicating that these genes likely represent false-positive results. Only FAM77C and THCI981357 (decreased in sensitive) and MSRA (increased in sensitive) differentially regulated sensitive and resistant cell lines with statistical significance in both panels. THCI981357 does not encode a known protein. MSRA is a methionine sulfoxide reductase felt to be important in the repair of oxidative damage (32). FAM77C (also NKAIN1) is known to interact with the β1 subunit of the Na/K-ATPase and is felt to have relevance in neuronal signaling (33). The mechanism linking either of these genes to response to selumetinib is unclear.

In conclusion, these data suggest that further development of selumetinib in patients whose tumors harbor ras or raf (and perhaps MEKI) mutations should be undertaken. The optimal trial design to test this hypothesis would select NSCLC and breast cancer patients with mutant ras or raf, respectively. Currently, a prospective study is under way to address this question (NCT00890825). It will be important in this study to evaluate biological (including ras/raf/MEK/ERK and PI3K/mTOR/akt pathway analysis) as well as clinical end points to evaluate subpopulations of tumors that respond to MEK inhibition with selumetinib.

Disclosure of Potential Conflicts of Interest

Tim French and Paul Smith are full-time employees of AstraZeneca. Dennis J. Slamon receives research funding from AstraZeneca, including funding to support this work. Dr. Richard S. Finn and Dr. Edward B. Garon receive research funding from AstraZeneca for clinical trials, including clinical trials with selumetinib (AZD6244), but did not receive research funding for this preclinical research.

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