Oncogenes and Tumor Suppressors

Molecular Dissection of AKT Activation in Lung Cancer Cell Lines

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Abstract

AKT is a critical signaling node downstream of phosphoinositide 3-kinase (PI3K), which is often activated in cancer. We analyzed the state of activation of AKT in 80 human non–small cell lung carcinoma cell lines under serum starvation conditions. We identified 13 lines, which showed persistent AKT activation in the absence of serum. In 12 of 13 lines, AKT activation could be attributed to loss of PTEN, activating mutation in EGFR receptor (EGFR) or PIK3CA, or amplification of ERBB2. HCC2429 was the only cell line that had no alterations in those genes, but had high phospho-AKT(Ser473) levels under serum starvation conditions. However, the activation of AKT in HCC2429 was PI3K– and mTOR complex 2 (mTORC2)-dependent based upon use of specific inhibitors. Kinome tyrosine phosphorylation profiling showed that both Notch and SRC were highly activated in this cell line. Despite the activation of Notch, AKT activation and cell survival were not affected by Notch inhibitors DAPT or compound E. In contrast, SRC inhibitors PP2 and dasatinib both significantly decreased pAKT(Ser473) levels and reduced cell survival by inducing apoptosis. Furthermore, a combination of SRC and mTOR inhibition synergistically blocked activation of AKT and induced apoptosis. Overexpression of SRC has been identified previously in human lung cancers, and these results suggest that a combination of SRC and mTOR inhibitors may have unique therapeutic benefit for a subset of lung cancers with these molecular features. Mol Cancer Res; 11(3): 282–93. ©2012 AACR.

Introduction

Lung cancer is the leading cause of cancer-related deaths in both the United States and worldwide with a 5-year survival rate of only 15% (1). Lung cancer consists of several pathologic subtypes, including adenocarcinoma, squamous cell carcinoma, small cell carcinoma, and large cell carcinoma. Those types not including small cell carcinoma are often grouped together as non–small cell lung carcinoma (NSCLC). Cancer genome sequencing efforts have identified many recurrent mutations that seem to contribute to human lung cancer development (2, 3). In adenocarcinoma, several proto-oncogenes, including KRAS and EGFR, are known to be mutated at significant frequency (3–5). Mutation of tumor suppressors including TP53, CDKN2A, PTEN, NF1, and LKB1 are also common in lung adenocarcinoma (3, 6). The PI3K/AKT/mTOR pathway, which plays multiple roles in cell growth, proliferation, and survival, is frequently deregulated in cancer. The most common mechanism of activation of this pathway in cancer is due to loss or reduced expression of PTEN in multiple cancer types (7, 8). However, several other activating mechanisms/mutations are known, including PIK3CA and AKT1 mutation, and activation of upstream tyrosine kinases including EGFR receptor (EGFR; ref. 9).

Phosphoinositide 3-kinase (PI3K) consists of a regulatory p85 subunit and a catalytic p110 subunit, which phosphorylates lipid inositides at the 3′ position (9). PI3K activation results in the generation primarily of the second messenger phosphatidylinositol (3,4,5)-trisphosphate (PIP3). PIP3, in turn recruits both AKT and PDK1 to the membrane, where PDK1 phosphorylates AKT at the T308 site. AKT is also phosphorylated at S473 by mTOR complex 2 (mTORC2) inactivates its Rheb GTPase activity, leading to activation of mTOR complex 1 (mTORC1; refs. 13, 14). Phosphorylation of TSC2 by AKT inactivates its Rheb GTPase activity, leading to activation of mTOR complex 1 (mTORC1; refs. 13, 14). mTORC1 phosphorylates a number of downstream proteins including the S6 kinases and eIF4E-binding proteins (4EBP; ref. 15). Together, these effects lead to ribosome and protein biogenesis, cell size increase, and preparation for cell division.
and growth. mTORC1 phosphorylation of S6kinase and Grb10 also lead to negative feedback to diminish both PI3K and AKT activation (16–19). The critical role of S473-phosphorylation of AKT in its activation and the possibility that constitutive AKT might represent a major therapeutic target in a subset of NSCLC led us to pursue the following studies. We examined the frequency of constitutive activation of AKT in a large series of NSCLC cell lines, using pAKT(S473) as an indicator of AKT activation. We found that AKT activation in serum-deprived conditions is not common among lung cancer cell lines and correlates with activating mutation in either EGFR or PIK3CA, loss of PTEN, or amplification of ERBB2. However, 1 NSCLC line with persistent AKT activation had none of these findings and was examined in detail.

Materials and Methods

Reagents

Wortmannin and LY294002 were purchased from Biomol Research Laboratories. Torin1/2 and afatinib were kindly provided by Nathanael S. Gray and Pasi A. Jänne, respectively (Dana-Farber Cancer Institute, Boston, MA). PP242, DAPT, and PP2 were obtained from EMD Chemical. Compound E was purchased from AXXORA, LLC. Dasatinib, lapatinib, and rapamycin were obtained from LC laboratories. MK-2206 was from Selleck. Cell culture media RPMI-1640 was from Cellgro and supplements were from Invitrogen.

Cell culture

Eighty NSCLC cell lines were used in this study, as described previously (20). These were obtained from Matthew Meyerson (Dana-Farber Cancer Institute, Boston, MA) 5 years ago, who fingerprinted them by single-nucleotide polymorphism (SNP) arrays to establish that they were unique. Fresh stocks of these cell lines were used repeatedly to avoid accumulation of clonal mutations. All cell lines were maintained in standard media as described. HCC2429, HCC15, HCC1833, and H3255 cells were maintained in RPMI-1640 supplemented with 10% FBS and 1% penicillin–streptomycin in an incubator at 37°C with 5% CO2. For serum starvation, cells were cultured in the absence of serum for 24 hours.

Immunoblotting

Cells were harvested in lysis buffer consisting of 50 mmol/L Tris–HCl (pH 7.5), 150 mmol/L NaCl, 1% Triton X-100, 1 mmol/L EDTA, 1 mmol/L EGTA, and a cocktail of protease inhibitors (Sigma-Aldrich). Cell lysates were clarified by centrifugation for 5 minutes and the protein concentration of the supernatants was determined using a modified Bradford assay (Bio-Rad). For immunoblotting, 20 μg of protein was loaded in each lane, and was separated by SDS-PAGE on 4% to 12% gradient gels (Invitrogen), transferred to polyvinylidene difluoride (PVDF) membranes and detected by immunoblotting with the following primary antibodies: TSC1, pAKT(S473), AKT, AKT1, AKT2, extracellular signal–regulated kinase (ERK), pERK(T202/Y204) glyceraldehyde-3-phosphate dehydrogenase (GAPDH), pS6(S240/244), S6, PTEN, pSRC(Y416), SRC, and cleaved caspase-3 (Cell Signaling Technology); TSC2 (Santa Cruz Biotechnology); hairy and enhancer-of-split 1 (Hes1; Chemicon). Goat anti-mouse and anti-rabbit secondary antibodies (Santa Cruz Biotechnology) conjugated to horseradish peroxidase (HRP) were used at a 1:3,000 dilution and immunoreactive bands were detected by chemiluminescence (SuperSignal, Pierce) and exposure to film (Denville Scientific).

Immunoprecipitation

For immunoprecipitation experiments, 500 μg of clarified cell lysate were preabsorbed with 50 μL of protein A/G Sepharose (GE Healthcare) for 1 hour at 4°C, and then incubated overnight at 4°C with 1 μg of antibody. Immune complexes were precipitated with 50 μL of Protein A/G Sepharose for 1 hour and then washed 3 times with lysis buffer. Immunoprecipitated proteins were eluted in Laemmli sample buffer, separated by SDS-PAGE, and immunoblotted as outlined earlier. For the interaction between mTOR and Raptor or Rictor, CHAPS lysis buffer [40 mmol/L HEPES (pH 7.5), 120 mmol/L NaCl, 1 mmol/L EDTA, 10 mmol/L sodium pyrophosphate, 10 mmol/L β-glycerophosphate, 0.5 mmol/L sodium orthovanadate, 0.3% CHAPS] was used for cell lysis and immunoprecipitation buffers.

Cell viability assay

Cells were plated in sterile 96-well plates and cultured overnight. Compounds were then added in serial dilutions. Cellular viability was determined after 48 hours using Vybrant MTT Cell Proliferation Assay Kit (Invitrogen). Plates were measured on a THERMOmax microplate reader (Molecular Devices). All measurements were conducted in triplicate. Cell viability is expressed as percentage of that seen in vehicle-treated control wells, and SEs for measurements were determined.

Statistical analysis

Quantitative data are reported as the mean ± SEM from at least 3 independent experiments. The means for various treatment groups were compared using ANOVA and Dunnett post hoc test.

Kinome tyrosine kinase phosphorylation profiling

Luminex immunosandwich assays were conducted as previously described (21) with the following modifications. Antibodies were conjugated to Luminex MagPlex microspheres (Luminex). Assays were carried out in 384-well ThermoMatrix square bottom plates (Thermo) in conjunction with a 96-well (CyBio) and a 384-well (BioMek) liquid handler. The data were acquired with a FlexMap 3D instrument (Luminex) according to the manufacturer’s instructions. The raw data were normalized by subtracting sample and antibody backgrounds. A normalized value more than 10 was considered positive. Marker selection and heatmap generation were conducted with GENE-E software (http://www.broadinstitute.org/cancer/software/GENE-E/).
Mutations
We conducted Oncomap mutation analysis by mass spectrometry on the HCC2429 cell line, conducting 1,047 assays interrogating 983 unique mutations in 115 genes (22).

Ethics statement
All procedures were carried out in accordance with the Guide for the Humane Use and Care of Laboratory Animals, and the study was approved by the Animal Care and Use Committee of Children’s Hospital, Boston, MA.

In vivo tumorigenicity
HCC2429 cells (2.5 × 10⁶) suspended in 50% Matrigel (BD Bioscience) were injected subcutaneously into both flanks of severe combined immunodeficient (SCID; C.B-17) mice. When tumors were palpable (>5-mm diameter), the mice were randomized to treatment with placebo, dasatinib (5 mg/kg), Torin2 (10 mg/kg) or dasatinib (5 mg/kg) + Torin2 (10 mg/kg) by oral gavage in a volume of 0.1 mL for 5 days a week. The tumor size was measured 3 times per week with a caliper. Tumor volume was calculated with the formula: volume = (length) × (width)²/2. Relative tumor volume was calculated for each mouse for each tumor using this formula, based on tumor volume on the first day of treatment. Mice were sacrificed 12, 14, 17, and 17 days after initiation of treatment for vehicle, dasatinib, Torin2, and combined treatment mice, respectively, as the endpoint of the therapeutic trial. A separate set of mice were used to generate tumor xenografts and treated for 3 days only to assess biochemical effects of treatment.

Immunohistochemistry
After paraffin removal and hydration, 8-μm paraffin sections were treated with Target Retrieval Solution pH 6.1 (Dako), blocked with 3% H₂O₂ in methanol to quench endogenous peroxidase, and then put in 5% normal goat serum in 0.1% Triton X in PBS. After slides were rinsed 3 times, sections were incubated with primary antibodies overnight at 4°C, washed, and incubated with secondary antibody conjugated with HRP. 3,3′-Diaminobenzidine (DAB) Chromogen solution (Envision+ System Dako) was

Figure 1. Lung cancer cell lines with high pAKT(S473) under serum starvation conditions. A–D, Immunoblots are shown for 19 lung cancer cell lines after 24 hours of serum starvation (−) or 30 minutes after serum addback after serum starvation (+), for multiple components of the AKT-mTOR signaling pathway. Thirteen cell lines show constitutive, high levels of pAKT(S473) during serum starvation. Six can be seen to be null (H1650, H1781, H157, HCC2935, and HCC461) or markedly reduced (H2444) in PTEN expression. Four cell lines are controls and show normal regulation of pAKT(S473) levels.
then applied to generate a color reaction. Slides were then counterstained with hematoxylin (Dako). Antibodies used for staining were: anti-pSRC(Y416; 1:100, Cell Signaling Technology), anti-pAKT(S473; 1:100, Cell Signaling Technology), anti-pS6(S235/236; 1:100, Cell Signaling Technology).

Results

Constitutive activation of AKT in lung cancer cell lines

To elucidate the frequency and mechanisms of constitutive AKT activation in human lung cancer, we analyzed 80 NSCLC cell lines (Supplementary Table S1) that we have studied previously (20). Immunoblot analysis identified 13 cell lines in which phospho-AKT at Ser473 [pAKT(S473)] levels were high in serum-starved conditions indicating constitutive activation of AKT (Fig. 1A–D). These cell lines had been subject to genomic characterization previously, including analysis for mutations in KRAS, EGFR, PIK3CA, PTEN, and LKB1 (ref. 4; Table 1). Six of 13 lines with elevated pAKT(S473) levels during starvation had no expression of PTEN by immunoblotting, likely due to PTEN gene mutations, deletion, or methylation silencing (Fig. 1). Three of 13 lines had KRAS mutation, 1 had a PIK3CA mutation, 5 had EGFR mutations (Table 1), and 2 had HER2 amplification (Table 1 and Supplementary Fig. S1). One or 2 of these 3 mutations were identified in 12 of 13 lines with constitutive AKT activation. A single line, HCC2429, had no mutations in any of these 3 genes. To confirm that HCC2429 had none of the common mutations in these genes, we assessed the OncoMap panel of 983 mutations in 115 genes (22), and again found no mutations of any kind. HCC2429 was established from a 34-year-old, nonsmoking woman, and was found to have a t(15;19)(q11;p13) translocation involving the Notch3 gene, leading to overexpression of Notch3 (23). Thus, our analysis focused on understanding the mechanism of constitutive AKT activation in HCC2429.

AKT activation in HCC2429 is dependent on both PI3K and mTORC2

To dissect the mechanism of AKT activation in HCC2429 cells, we pursued several experimental approaches. We examined whether all 3 AKT isoforms were activated. HCC2429 cells expressed only 2 AKT isoforms, AKT1 and AKT2. Immunoprecipitation-immunoblotting experiments showed that each of AKT1 and AKT2 were phosphorylated at the S473 site, suggesting that AKT activation was due to upstream effects that were not isoform specific (Fig. 2A and B). PI3K inhibitors LY294002 and Wortmannin completely eliminated and significantly reduced pAKT(S473) levels, respectively, independent of serum treatment, suggesting AKT activation was downstream of PI3K (Fig. 2C and D). These data suggest that PI3K activity was required for the activation of AKT seen in HCC2429. These observations are consistent with the current model of AKT activation in which 3-phosphoinositide levels regulate T308 phosphorylation by PDK1, which is followed by S473 phosphorylation (10, 11).

Because mTORC2 is known to be the proximate kinase, which phosphorylates AKT at the S473 site (10), we examined the effects of mTORC2 inhibitors on AKT phosphorylation in HCC2429 cells. Both PP242 and Torin1, ATP-

| Table 1. Histology, mutation status, and PTEN expression of 13 NSCLC lung cancer cell lines with high pAKT(S473) under serum starvation conditions |
|---|---|---|---|---|---|
| **Histology** | **PTEN mutation** | **PIK3CA mutation** | **KRAS mutation** | **EGFR mutation** | **Other** | **PTEN expression**
| Calu-3 | Adenocarcinoma | WT | WT | WT | WT | HER2 CN gain (50)
| H157 | Squamous | G251C (38) | WT | G12R (4) | WT | LKB1 LOH (51) | None
| H820 | Adenocarcinoma | N/A | WT | WT | E746_T751del, T790M (4) | None
| H1650 | Adenocarcinoma, Bronchoalveolar | N/A | WT | WT | E746_A750del (4) | None
| H1781 | Bronchoalveolar | N/A | WT | WT | WT | HER2_G776insV (4) | None
| H1819 | Adenocarcinoma | WT | WT | G12V (4) | WT | HER2 CN gain (50) | None
| H2444 | NSCLC | N/A | WT | G12V (4) | WT | None
| H3255 | Adenocarcinoma | N/A | WT | WT | L858R (4) | None
| HCC461 | Adenocarcinoma | N/A | WT | G12D (4) | WT | None
| HCC2429 | NSCLC | N/A | WT | WT | WT | None
| HCC2450 | Squamous | N/A | H1047R (4) | WT | WT | None
| HCC2935 | Adenocarcinoma | N/A | WT | WT | E746_A750del, T751A (4) | None
| PC9 | Adenocarcinoma | WT | WT | WT | E746_A750del (4) | None

Abbreviations: CN, copy number; N/A, not available; WT, wild-type. *Observations made here (Fig. 1).
competitive inhibitors of mTOR kinase activity, which inhibit both mTORC1 and mTORC2 (24, 25), completely eliminated pAKT(S473) levels in HCC2429 cells (Fig. 3A). In contrast, rapamycin had more complex effects on pAKT(S473) levels (Fig. 3B). pAKT(S473) was reduced slightly after 1 hour of treatment in the absence of serum, when mTORC1 inhibition of pS6(S240/244) levels was already complete. Greater reduction in pAKT(S473) levels was seen with 24 hours of rapamycin treatment both with and without serum (Fig. 3B). Immunoprecipitation experiments showed that Raptor binding to mTOR, in mTORC1, was eliminated by an hour of rapamycin treatment at 50 nmol/L; while in contrast, Rictor binding to mTOR, in mTORC2, required greater than an hour of rapamycin treatment to be significantly reduced, similar to previous observations (26). Thus, phosphorylation and activation of AKT at S473 is due to mTORC2 activity, and can be reduced by both ATP-competitive inhibitors of mTOR and long-term treatment with rapamycin.

Tyrosine kinase profiling indicates that SRC and Notch pathways are highly active in HCC2429 cells

The finding that activation of AKT was PI3K- and mTORC2-dependent in the absence of PI3KCA or AKT mutation suggested that upstream kinase activation was driving PI3K in HCC2429 cells. To screen for kinases activating AKT, we conducted bead-based profiling of tyrosine kinase phosphorylation (see Materials and Methods; ref. 21). The relative phosphorylation level of each kinase included in this assay is shown in Fig. 4. Control cells that were tested in the assay included H3255 cells, which have an EGFR activating mutation, and H3255 lysates showed high values for EGFR and downstream kinases, as expected. Both Notch1 and SRC family kinases, including SRC and YES1, were highly phosphorylated in HCC2429 cells, independent of rapamycin treatment, and were enhanced to a small extent by the absence of serum (Fig. 4 and Supplementary Table S2). This suggested that the Notch and SRC pathways were activated in HCC2429 cells and the possibility that they contributed to the activation of AKT. As noted earlier, Notch3 activation was identified in HCC2429 when they were first isolated (23), so that Notch pathway activation was expected. The Notch pathway has been implicated both upstream and downstream of mTOR in previous studies (27, 28). Because rapamycin treatment had little effect on phosphorylation of these proteins in HCC2429, it seems that these phosphorylation events were independent of mTORC1 in these cells. Although several other tyrosine kinases showed some increase in phosphorylation in this assay, including HCK, ABL1, and SYK, they were not examined further because the magnitude of the change was much less than that seen for Notch1, SRC, PTK6, and YES1 (Supplementary Table S2).
AKT activation in HCC2429 is SRC family dependent but not Notch dependent

We then investigated whether Notch- or SRC-dependent signaling was leading to activation of PI3K-AKT pathway in HCC2429 cells. Two specific γ-secretase inhibitors, compound E and DAPT (29), were applied to HCC2429 cells, and had no effect on levels of pAKT(S473; Fig. 5A and B). Indeed, at some doses, these compounds led to an increase in pAKT(S473) levels. Confirmation of activity of these drugs is indicated by the reduction in levels of Hes1, which is a known transcriptional target of Notch signaling (23). Furthermore, treatment with DAPT or compound E had little or no growth inhibition effect in any of the HCC15, HCC2429, and H3255 lines (Fig. 5C). These results suggested that although Notch pathway is highly active in HCC2429 cells, it is not the activator of PI3K-AKT pathway and its inhibition has no effect on cell survival. SRC tyrosine family kinases are key regulators of cellular proliferation, survival, motility, and invasiveness (30). Of all of the SRC-family kinases including SRC, FYN, YES, LCK, and LYN; SRC is the one that is most often implicated in cancer. SRC can activate the PI3K-AKT pathway, which is important for survival and proliferation (31). To examine the role of SRC signaling in both the elevation of pAKT(S473) levels and cell growth, we used both PP2 (32), a selective inhibitor of SRC family kinases, and dasatinib, a multi-BCR/ABL and SRC family tyrosine kinase inhibitor (33). Both PP2 and dasatinib markedly reduced pAKT(S473) levels in the absence of serum in HCC2429 cells (Fig. 5D). However, the effects of these inhibitors on pAKT(S473) were less dramatic in serum (Fig. 5E), consistent with some activation of AKT by serum by a mechanism independent of SRC. Both drugs also

Figure 3. AKT activation in HCC2429 is mTORC2 dependent. A, HCC2429 cells were treated with mTOR inhibitor PP242 (2.5 μmol/L) or Torin1 (250 nmol/L) for 24 hours in the presence or absence of serum and analyzed by immunoblotting. B, HCC2429 cells were treated with rapamycin for either 1 or 24 hours with the indicated doses in the presence or absence of serum and analyzed by immunoblotting. C, HCC2429 cells were treated with rapamycin for the indicated times and doses in the presence or absence of serum for 24 hours followed by immunoprecipitation (IP) with mTOR antibody and analyzed by immunoblotting.
eliminated pSRC-Y416 levels and induced cell death as shown by an increase in cleaved caspase-3 in the absence of serum. Cell growth assays showed that both drugs significantly reduced cell growth after 48 hours of treatment (Fig. 5F), although many cells survived.

Note that the H3255 lung cancer cell line was even more sensitive to SRC inhibitor treatment than HCC2429 cells (Fig. 5F). H3255 cells have the EGFR L858R-activating mutation, and similar to other EGFR- and ERBB2-mutant cell lines show constitutive phosphorylation of ERK1/2 (Supplementary Fig. S2A). They also show high-level phosphorylation of SRC, similar to HCC2429 cells, and marked response to dasatinib treatment with loss of pSRC, pAKT, and phospho-ERK (pERK; Supplementary Fig. S2B). Similar observations have been made previously on SRC activation and inhibitor sensitivity in EGFR-mutant lung cancer cell lines (34). These results are consistent with the apoptotic effect of EGFR inhibitor lapatinib or gefitinib on EGFR-dependent H3255 lung cancer cells (Supplementary Fig. S3B). However, EGFR inhibitors had no effects on either pAKT levels (Supplementary Fig. S3A) or cell viability (Supplementary Fig. S3B) in HCC2429 cells, suggesting that SRC inhibitors reduced pAKT levels and cell survival independent of EGFR in HCC2429 cells.

To summarize, our data indicate that activation of the PI3K-AKT pathway in HCC2429 cells was SRC- but not Notch-dependent, and that SRC inhibition reduced growth of these cells.

SRC and mTOR inhibition in HCC2429 synergistically inactivate AKT and reduce cell survival

Although SRC overexpression and activation commonly occur in NSCLC, SRC inhibitors alone have had relatively poor results in NSCLC clinical trials (35). Cell lines with EGFR mutations are particularly sensitive to SRC inhibition in vitro (36). For these reasons, as well as the partial growth inhibition seen with dasatinib, we explored combination treatment of the HCC2429 line. We chose to combine the SRC inhibitors with Torin1, as it is a specific catalytic site inhibitor of mTORC2 (25) and reduces AKT phosphorylation substantially (Fig. 3). At lower doses, PP2, dasatinib, and Torin1 alone only partially decreased pAKT(S473) levels. However, the combination of Torin1 with either PP2 or dasatinib completely eliminated pAKT(S473) levels in HCC2429 cells (Fig. 6A). Concordant with the pAKT(S473) effect, the combination treatments caused a more striking reduction in cell numbers than either drug alone in HCC2429 cells (as well as H3255 cells; Fig. 6B and C). Combination treatment also induced apoptosis more strongly than individual drugs, as indicated by increased cleaved caspase-3 (Fig. 6A). In contrast, there was no synergy among these drugs for the HCC15 cells, although Torin1 had some effect. Because mTOR kinase inhibitors are still in early-phase clinical trials, we also examined whether rapamycin or everolimus, U.S. Food and Drug Administration (FDA)-approved compounds, might have similar effects on the growth of HCC2429 cells. Indeed, both of these mTORC1 inhibitors had similar
effects in reducing viability of HCC2429 cells when applied in combination with dasatinib (Supplementary Fig. S4).

We then examined the benefit of these drugs in vivo using HCC2429 xenografts. Although each of dasatinib and Torin2 delayed tumor growth in this system, combination treatment with the 2 drugs had a greater effect (Fig. 7A–D). To confirm that these drugs were hitting their intended molecular targets in these mice, immunohistochemistry...
staining was conducted. Levels of pSRC(Y416) were marked reduced in HCC2429 tumors from mice treated with dasatinib, and were not changed in mice treated with Torin2. Levels of pAKT(S473) and pS6(S235/236) were somewhat decreased in mice treated with either dasatinib or Torin2 alone, but were more strongly reduced in mice treated with a combination of both drugs (Fig. 7E). Thus, combination treatment with SRC and mTOR inhibitors synergistically reduced HCC2429 tumor cell growth in vivo.

Discussion

Here, we report the analysis of AKT phosphorylation and activation in 80 NSCLC cell lines. We found persistent elevated levels of pAKT(S473), the site of phosphorylation by mTORC2, during serum starvation in 13 cell lines. Previous studies have shown that phosphorylation of AKT at the S473 site correlates with AKT kinase activity in in vitro studies, including in lung cancer cell lines (37). We found AKT activation without serum in the minority of cell lines studied, 13 of 80 (16%) in marked contrast to an earlier report [16 of 17 (94%); ref. 37]. We suspect that this difference may be attributed to our more stringent serum deprivation (24 hours vs. overnight) and the complete lack of serum (0% vs. 0.1%) in comparison with the previous study (37). The cell lines examined in our study were also different from those studied previously.

Twelve of 13 cell lines had genetic findings that explained their constitutive activation of AKT: either activating mutation in EGFR, PIK3CA, or AKT and in which the expression of PTEN was genetic nor other evidence of activating mutation in EGFR, PIK3CA, or AKT and in which the expression of PTEN was abundant. Tyrosine kinase activity profiling led to the identification of activation of Notch and SRC pathways in HCC2429 cells. While Notch inhibition had little effect on pAKT(S473) levels or on growth or survival of these cells, SRC inhibition with dasatinib or PP242 led to significant growth inhibition. Furthermore, combined treatment with either of those compounds and any of 4 different mTOR inhibitors, both rapalogs or ATP-competitive mTOR kinase inhibitors, led to synergistic reduction in pAKT(S473) levels, growth inhibition, and cell death (Fig. 6 and Supplementary Fig. S4). Furthermore, the combination of Torin2 and dasatinib led to synergistic reduction in tumor growth in vivo (Fig. 7).

The HCC2429 cell line was originally derived from a 34-year-old nonsmoking woman with adenocarcinoma of the lung (23), and has been subject to extensive studies. It was originally described as having a t(15;19) translocation, which originally described as having a t(15;19) translocation, which...
activation in HCC2429 cells (23). In contrast, we found that although there was activation of the Notch pathway in these cells, assessed by expression of Hes1, inhibition of the Notch pathway by DAPT or compound E had no effect on pAKT levels in either the absence or the presence of serum (Fig. 5).

The nonreceptor protein tyrosine kinase SRC plays a crucial role in signal transduction pathways involved in cell division, motility, adhesion, and survival in both normal and cancer cells (30, 40). Overexpression of the SRC protein and an increase in its specific activity have been observed in numerous cancer types (41). In NSCLC, 123 of 370 (33%) of biopsy samples showed expression of pSRC (Y416) by immunohistochemical analysis (34). SRC can be activated by receptor tyrosine kinases including the EGFR. SRC can also be activated by interaction with viral proteins, although there is no evidence for this occurrence in human cancer.

Figure 7. Synergistic effects of dasatinib and mTOR inhibitors on HCC2429 xenografts. HCC2429 cells were injected into both flanks of SCID (C.B-17) mice to generate tumors. When tumors were palpable, mice were treated with placebo, dasatinib (5 mg/kg), Torin2 (10 mg/kg), or dasatinib (5 mg/kg) + Torin2 (10 mg/kg) by oral gavage 5 days a week. N = 3–5 mice per treatment group. Mice were sacrificed 12, 14, 17, and 17 days after initiation of treatment of vehicle, dasatinib, Torin2, and combined treatment mice, respectively. A, representative HCC2429 xenograft tumors. B, relative tumor volume during treatment. C, tumor weight at the end of treatment. D, tumor volume at the end of treatment. E, immunohistochemical staining for pSRC(Y416), pAKT(S473), and pS6 (S240/244) after 3 days of treatment, in a separate set of SCID mice.
There is only one naturally occurring activating mutation of SRC that has been identified (Q531E), despite large-scale human genome sequencing projects. This mutation results in truncation and deregulated activation of the SRC protein, but is rare, being seen in only 1% of all colorectal cancer and never reported in other common malignancies (42).

SRC can activate the PI3K-AKT, mitogen-activated protein kinase (MAPK), and JAK-STAT signaling pathways that are critical for cell-cycle progression, survival, and proliferation (31). How SRC is activated in HCC2429 cells requires further investigation. Although SRC can activate the MAPK pathway, there was no detectable pERK1/2 in HCC2429 cells under serum starvation conditions (Supplementary Fig. S2A), suggesting that PI3K-AKT is the major pathway downstream of SRC, which contributes to tumorigenesis in this cell line.

Dasatinib is an oral multi-BCR/ABL and SRC family tyrosine kinase inhibitor approved for use in patients with chronic myelogenous leukemia and Philadelphia chromosome-positive acute lymphoblastic leukemia. It is being evaluated for use in numerous other cancers, including advanced lung cancer. However, a recent phase II clinical trial found that dasatinib as a single agent had modest clinical activity (35). Dasatinib arrests cell growth of lung cancer lines expressing wild-type or EGFR mutants that are resistant to EGFR inhibition. The combination of SRC inhibitor and EGFR inhibitor synergistically enhanced apoptosis in EGFR-dependent lung cancer cells, but had modest effects in EGFR-independent cells (34). However, dasatinib was shown to have no benefit when added to erlotinib treatment in patients with lung cancer with acquired resistance to erlotinib (43). mTOR is involved in protein synthesis, cell proliferation, and survival in cancer cells, and upstream signaling proteins that activate mTOR are often mutated in lung cancer, including EGFR, KRAS, PI3K, LKB1, PTEN, and AKT (4, 38, 44). Rapalogs, including temsirolimus and everolimus, which are allosteric inhibitors of mTORC1 through FKBP12 are in current clinical use for treatment of advanced renal cell carcinoma (45). The combination of mTOR inhibitors with other therapeutic agents often has synergistic effects in tumor growth inhibition in experimental models (46, 47). Our findings suggest that mTOR catalytic site inhibitors are potentially better drugs than rapamycin and analogs, through stronger and more direct inhibition of both mTORC1 and mTORC2, as well as dephosphorylation of 4E-BP1, which is not affected by rapamycin (48). Furthermore, our findings suggest that combination treatment including agents targeting kinases can be an effective strategy for lung cancer treatment. Given that SRC activation is common (~33% in human patients with lung cancer (34), a combination of a SRC and an mTOR inhibitor may be of significant benefit for a subset of these patients. Dasatinib has been shown to have a Cmax in the serum of 175 mmol/L in humans following a single dose (49), suggesting it could inhibit SRC effectively.

Although the EGFR-mutant cell line H3255 showed a dramatic response to dasatinib treatment (Fig. 5F), treatment of patients with lung cancer with EGFR mutation and acquired resistance to erlotinib with dasatinib showed no benefit (43), suggesting caution in translation of these findings to human subjects.

Disclosure of Potential Conflicts of Interest

No potential conflicts of interest were disclosed.

Authors’ Contributions

Conception and design: Y. Guo, D.J. Kwiatkowski

Development of methodology: Y. Guo, J. Du, D.J. Kwiatkowski

Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): Y. Guo, J. Du, D.J. Kwiatkowski

Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): Y. Guo, J. Du, D.J. Kwiatkowski

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Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): D.J. Kwiatkowski

Study supervision: D.J. Kwiatkowski

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