Distinct Interactions Between c-Src and c-Met in Mediating Resistance to c-Src Inhibition in Head and Neck Cancer

Banibrata Sen1, Shaohua Peng1, Babita Saigal1, Michelle D. Williams1,2, and Faye M. Johnson1,3

Abstract

**Purpose:** c-Src inhibition in cancer cells leads to an abrogation of invasion but a variable effect on apoptosis. The pathways downstream of c-Src promoting survival are not well characterized. Because cancer therapy that both decreases invasion and induces significant apoptosis would be ideal, we sought to characterize the mechanisms of resistance to c-Src inhibition.

**Experimental Design:** c-Src was inhibited in a panel of oral cancer cell lines and subsequent survival and signaling measured. The interactions between c-Src and c-Met were evaluated using immunoprecipitation and an in vitro kinase assay. Cytotoxicity was measured and the Chou–Talalay combination index calculated. An orthotopic model of oral cancer was used to assess the effects of c-Met and c-Src inhibitors.

**Results:** Inhibition of c-Src resulted in c-Met inhibition in sensitive cell lines, but not in resistant cell lines. Isolated c-Met was a c-Src substrate in both sensitive and resistant cells, but there was no interaction of c-Src and c-Met in intact resistant cells. To examine the biological consequences of this mechanism, we demonstrated synergistic cytotoxicity, enhanced apoptosis, and decreased tumor size with the combination of c-Src and c-Met inhibitors.

**Conclusions:** Sustained c-Met activation can mediate resistance to c-Src inhibition. These data suggest that the differences between c-Met and c-Src signaling in sensitive and resistant cells are due to distinct factors promoting or inhibiting interactions, respectively, rather than to intrinsic structural changes in c-Src or c-Met. The synergistic cytotoxic effects of c-Src and c-Met inhibition may be important for the treatment of head and neck cancers. *Clin Cancer Res;* 17(3); 514–24. ©2010 AACR.

Introduction

All epithelial tumors pose formidable challenges in clinical practice, but the anatomy of tumors in the head and neck region makes them particularly difficult to treat. Approximately 45,000 new cases of head and neck cancer are diagnosed in the United States each year, and the estimated worldwide incidence is 500,000 (1). The incidence and survival statistics are only half of the story, however; cancer- and treatment-induced distortions of anatomy and physiology have a profound impact on important functions such as eating, speaking, and hearing, and distortions in facial appearance contribute to social isolation in survivors. Although novel approaches have improved locoregional control in patients with advanced head and neck squamous cell carcinoma (HNSCC), locoregional and distant recurrence remains common and is almost always fatal. Thus, there is a great need to improve systemic therapy for patients with these tumors to increase cure rates and reduce morbidity.

The most successful targeted molecular therapeutic approach is inhibition of oncogene targets, particularly tyrosine kinases. One potential oncogene target in HNSCC is the c-Src family of nonreceptor tyrosine kinases (SFKs) (2, 3). Aberrant activation of c-Src has been demonstrated in numerous epithelial tumors, including HNSCC. c-Src regulates multiple signaling cascades that control diverse biological processes, and its inhibition in cancer cells can lead to reduced anchorage-independent growth, proliferation, survival, invasion, migration, metastasis, and tumor vascularity (2). In epithelial cancers, however, several researchers have observed that, while c-Src inhibition decreases migration and invasion, it has little effect on proliferation or apoptosis (4–6). In 10 of 12 colon cancer cell lines, complete inhibition of c-Src activity did not affect cell proliferation, although it did inhibit adhesion and migration (7). Similarly, c-Src inhibition in pancreatic cancer cells had no effect on cell cycle progression but completely inhibited migration and angiogenesis (8). We demonstrated that c-Src inhibition resulted in a universal and profound reduction of invasion and migration of all...
Translational Relevance

Although invasion is important in the pathophysiology of many cancers, local invasion is critical in head and neck cancers as a determinant of both morbidity and mortality, as it is associated with poorer locoregional control and decreased survival. Cancer therapy that both induces significant apoptosis and decreases invasion would be ideal for head and neck cancer. Because c-Src inhibition leads to profoundly diminished invasion with only moderate effects on survival and proliferation, we sought to identify pathways leading to cytotoxicity downstream of c-Src. Here we demonstrate that sustained c-Met activation mediates cell survival following c-Src inhibition. We investigated the biological importance of this interaction and discovered that c-Src and c-Met inhibition were synergistic. Given that both c-Src and c-Met inhibitors are in clinical use, our studies are immediately relevant for human cancer treatment.

Materials and Methods

HNSCC cell lines, but produced cytotoxicity in only 4 of 9 HNSCC cell lines (9, 10). Clearly, c-Src can mediate distinct biological processes independently. This may be accomplished by differential effects of c-Src on its multiple downstream substrates.

Although the molecular mechanisms that mediate c-Src’s effects on migration have been well described (11), those that mediate proliferation and survival are less well defined. c-Src can mediate its effects on proliferation and survival via interactions with growth factor receptors as well as the ERK1/2, JAK/STAT, and phosphoinositide 3-kinase (PI3K) pathways. c-Src may activate the PI3K pathway by 3 distinct mechanisms: direct interaction and phosphorylation of Akt (12, 13); interaction and activation of PI3K (14, 15); and reversal of PTEN activity (16).

Because local invasion is a critical determinant of both morbidity and mortality for HNSCC, systemic therapy that both decreases local invasion and induces significant cancer cell cytotoxicity would be ideal. Given that c-Src inhibition already results in a significant decrease in invasion, we sought in this study to understand the mechanisms underlying the effects of c-Src inhibition on cancer cell survival. We studied several signaling pathways known to interact with c-Src and discovered a correlation between the biological effects of c-Src inhibition and downstream signaling effects on the receptor tyrosine kinase c-Met. c-Met is known to signal both upstream and downstream from c-Src. It mediates resistance to epidermal growth factor receptor (EGFR) inhibition in lung cancer (17, 18) and c-Src inhibition in gastric cancer cell lines (19). Activation of c-Met by its ligand hepatocyte growth factor (HGF) is observed in HNSCC cell lines and tumors (20, 21); this activation stimulates migration and invasion and inhibits apoptosis of HNSCC cells (20, 22–25). We hypothesized that persistent c-Met activation following c-Src inhibition mediates resistance to apoptosis and cell cycle arrest.

Cell culture

Human HNSCC cell lines were obtained from Dr. Jeffrey Myers (MD Anderson Cancer Center, Houston, Texas) and maintained as described previously (10). Short tandem repeat profiling was performed on cellular DNA submitted to the Johns Hopkins University Fragment Analysis Core facility (Baltimore, MD). All cell lines were validated by cross-comparing their allelic short tandem repeat patterns, generated with the PowerPlex 1.2 platform (Promega), to the American Type Culture Collection repository database. Cells were passed in culture no more than 6 months after being thawed from authenticated stocks.

MTT assay

Cytotoxicity was assessed by the MTT assay as described elsewhere (9). For each experimental condition, at least 4 wells were treated. Cytotoxic effects and the combination index were calculated by using the Chou–Talalay equation, which takes into account both the potency (IC50) and shape of the dose-effect curve (26–28), using CalcuSyn software (Biosoft).

Cell cycle and apoptosis assays

For the cell cycle analysis, cells were harvested, fixed, and stained with propidium iodide as previously described (29). DNA content was analyzed on a cytofluorimeter by fluorescence-activated cell sorting analysis (FACS, FACScan; Becton Dickinson) using ModFit software (Verity Software House). To analyze apoptosis, cells were fixed and subjected to terminal deoxynucleotidyl transferase biotinylatedUTP nick-end labeling (TUNEL) staining according to the manufacturer’s protocol (APO-BRDU kit; Phoenix Flow Systems Inc.) as described previously (29).

Transfection with small interfering RNA

Cells were harvested, washed, and suspended (×10^6 cells/100 mL) in Nucleofector-V solution (Amaxa), and
small interfering RNA (siRNA) (200 pmol/100 mL) was added. Cells were electroporated (U-31 Nucleofector program, Amaxa) and then immediately diluted with prewarmed 500 μL Dulbecco’s modified essential medium and plated onto 6-well plates. The medium was changed after 16 hours. All c-Src and c-Met siRNAs were pre-designed as sets of 4 independent sequences (siGENOME SMARTpool, Dharmacon Inc.). Controls included cells transfected with a nontargeting (scrambled) siRNA and mock transfected cells (i.e., no siRNA).

Immunoprecipitation and Western blot analysis

Western blot analysis and immunoprecipitation were performed as previously described (9, 29). Briefly, cells were subjected to lysis on ice and lysates centrifuged at 15,000 rpm for 5 minutes at 4°C. For the immunoprecipitation, equal amounts of the protein cell lysate supernatant (500 mg) were precleared with Protein A and C Sepharose beads (Invitrogen Corporation). The precleared lysate was incubated with 5 μg of either the agarose-conjugated c-Met or the c-Src primary antibody overnight. The immunoprecipitates containing agarose beads were washed 4 times with immunocomplex wash buffer [50 mmol/L Tris-HCl] (pH 7.5), 100 mmol/L NaCl, 1% Triton X-100, 1 mmol/L EGTA, 1 mmol/L EDTA, 1% glycerol, 20 μg/mL leupeptin, 10 μg/mL aprotonin, 1 mmol/L phenylmethylsulfonyl fluoride, 1 mmol/L sodium vanadate] and boiled with 1× sample buffer for 5 minutes. For both the immunoprecipitation and the Western blot, equal protein aliquots were resolved by sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE), transferred to nitrocellulose membranes, immunoblotted with primary antibody, and detected with horseradish peroxidase–conjugated secondary antibody (Bio-Rad Laboratories) and ECL reagent (Amersham Biosciences).

In vitro kinase assay

In vitro kinase assays were performed as previously described (29). Briefly, Tu167 and Osc-19 cells were incubated with 100 nM dasatinib, DMSO (vehicle control), or 2 μM PHA665752 for 7 hours before cells were subjected to lysis, and c-Met or c-Src was immunoprecipitated as described in the previous paragraph. The immunocomplexes were washed and resuspended in a kinase assay reaction buffer that contained 15 microCi [γ^32P]ATP. During the kinase assay, 100 nM dasatinib or 2 μM PHA665752 was added to their respective samples. The reaction was terminated after 30 minutes at room temperature with sample buffer, and boiled immunocomplexes were separated by 8% SDS-PAGE. Radiolabeled proteins were detected by autoradiography. When c-Src and c-Met were assayed together, both were independently immunoprecipitated and then the immunoprecipitated fractions were combined in the kinase assay.

Orthotopic nude mouse models

All animal procedures were done in accordance with the Institutional Animal Care and Use Committee’s policies.
inhibit SFKs in this isogenic resistant cell line (Fig. 2D). Dasatinib did not inhibit SFK in Tu167R1 even at elevated concentrations (200 nM), demonstrating that direct resistance of the target (i.e., SFK) to the drug is the mechanism for these cells’ insensitivity to the cytotoxic effects of dasatinib (Supplementary Fig. 1). Thus, we did not further study c-Src and c-Met interactions in Tu167R1.

Specific inhibition of c-Src leads to c-Met inhibition in sensitive HNSCC cells

To determine whether the inhibition of c-Met was due to inhibition of SFKs or to an off-target effect of dasatinib, c-Src was specifically depleted by using small interfering RNA (siRNA). In sensitive cells, c-Src knockdown led to substantial inhibition of c-Met, whereas in resistant cells, c-Src depletion did not affect c-Met activation (Fig. 2E). Similar to the results with dasatinib, specific c-Src knockdown led to inhibition of AKT in sensitive cells and not in resistant cell lines.

Baseline expression or activation of c-Src or c-Met did not predict biological response to SFK inhibitors

We hypothesized that cell lines with high basal levels of activated c-Src or c-Met would be more likely to be sensitive to SFK inhibition. We examined the basal expression and activation of these proteins in 8 HNSCC lines (Supplementary Fig. 2) that had previously been characterized (Table 1) and found no such correlation.

**c-Met is a c-Src substrate in both sensitive and resistant cell lines**

To determine if c-Met is a direct c-Src substrate, we incubated isolated c-Met, c-Src, or both from resistant cell lines with c-Src and measured c-Met activation. We found that c-Met was specifically phosphorylated only in the presence of c-Src, suggesting that c-Met is a direct c-Src substrate.

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**Table 1. IC₅₀ values for dasatinib in HNSCC cell lines**

<table>
<thead>
<tr>
<th>Cell line</th>
<th>Source</th>
<th>IC₅₀ (nM)</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tu167</td>
<td>Oral cavity, floor of mouth</td>
<td>45 ± 8</td>
<td>Sensitive</td>
</tr>
<tr>
<td>TR146</td>
<td>Oral cavity</td>
<td>67 ± 2</td>
<td>Sensitive</td>
</tr>
<tr>
<td>PCI-24</td>
<td>Oral cavity, tongue</td>
<td>53 ± 14</td>
<td>Sensitive</td>
</tr>
<tr>
<td>PCI-13</td>
<td>Oral cavity</td>
<td>96 ± 15</td>
<td>Sensitive</td>
</tr>
<tr>
<td>HN5</td>
<td>Oral cavity, tongue</td>
<td>140 ± 79</td>
<td>Intermediate</td>
</tr>
<tr>
<td>UMSCC47</td>
<td>Oral cavity, tongue</td>
<td>160 ± 34</td>
<td>Intermediate</td>
</tr>
<tr>
<td>UMSCC2</td>
<td>Oral cavity, alveolar ridge</td>
<td>180 ± 37</td>
<td>Intermediate</td>
</tr>
<tr>
<td>UMSCC15A</td>
<td>Oral cavity</td>
<td>186 ± 15</td>
<td>Intermediate</td>
</tr>
<tr>
<td>OSC19</td>
<td>Oral cavity</td>
<td>312 ± 36</td>
<td>Resistant</td>
</tr>
<tr>
<td>LN686</td>
<td>Oral cavity, tongue</td>
<td>324 ± 101</td>
<td>Resistant</td>
</tr>
<tr>
<td>Tu167R2</td>
<td>Oral cavity, floor of mouth</td>
<td>803 ± 189</td>
<td>Resistant</td>
</tr>
<tr>
<td>Tu167R1</td>
<td>Oral cavity, floor of mouth</td>
<td>&gt;1000</td>
<td>Resistant</td>
</tr>
<tr>
<td>Tu138</td>
<td>Oral cavity</td>
<td>&gt;5000</td>
<td>Resistant</td>
</tr>
</tbody>
</table>

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**Figure 1.** The effect of SFK inhibition on apoptosis and cell cycle in HNSCC cell lines. Cells were treated with vehicle control or 100 nM dasatinib for 24 hours and analyzed by TUNEL staining (A) or stained with propidium iodide and analyzed by FACS (B). The proportion of apoptotic cells or cells in each cell cycle phase is graphed as percentage of the total. Bars, SD. *P < 0.05 (B, for the effect on S-phase) versus vehicle control.
(Osc-19) and sensitive (Tu167) cell lines and measured kinase activity by an in vitro kinase assay. As expected, dasatinib and c-Met inhibitor PHA665752 inhibited c-Src and c-Met kinase activity respectively and specifically (Fig. 3A and B, lanes 1–6). In both cell lines, inhibition of c-Src led to decreased expression of phosphorylated c-Met
(Fig. 3A and B, lanes 7 vs. 8), but the inhibition of c-Met did not affect expression of phosphorylated c-Src (Fig. 3A and B, lanes 7 vs. 9). Furthermore, in the presence of PHA665752 and c-Src, c-Met was phosphorylated, confirming that c-Met is a direct c-Src substrate (Fig. 3A and B, lane 9) and acts as a downstream signaling molecule for c-Src kinase.

**c-Src and c-Met interactions are distinct in HNSCC cell lines**

Although the *in vitro* kinase assay demonstrated that c-Met is a c-Src substrate in both sensitive and resistant cell lines, c-Src knockdown or inhibition reduced c-Met activation in some HNSCC cell lines but not others. These data suggest that there is no intrinsic change in the c-Src or c-Met molecules, but that the interaction between c-Src and c-Met differs in sensitive and resistant intact cells. To investigate this possibility, we immunoprecipitated c-Met or c-Src from sensitive and resistant cells (Fig. 3C). In Tu167 cells, an interaction between c-Src and c-Met was demonstrated by the immunoprecipitation of both c-Src and c-Met. No such interaction was demonstrated in resistant cells.

**The effect of SFK inhibition on c-Met is not mediated via the release of ligand**

We examined whether the release of HGF mediates SFK’s effect on c-Met activation. In a panel of 6 HNSCC cell lines with diverse sensitivities to dasatinib (Tu167, Tu167R2, PCI13, Osc19, Tu138, and TR146), we did not detect HGF secretion by ELISA into the cell culture medium in control or dasatinib-treated cells (up to 48 hours incubation). Similarly, cellular levels of HGF did not change following dasatinib treatment in any of these cell lines (Fig. 4A).

Exogenous HGF led to the activation of c-Met on 4 distinct sites (Fig. 4A). In sensitive cells, dasatinib inhibited the phosphorylation of Y1234/1235 (activation loop), Y1365 (morphology/motility), and Y1349 (Gab1 binding) in both the presence and absence of exogenous HGF but did not affect Y1003 (ubiquitination). All cell lines expressed the adaptor protein Gab1.

**EGFR contributes to c-Met activation in resistant cell lines**

Previous reports have demonstrated cross-talk between EGFR and c-Met. To determine if EGFR contributes to c-Met activation in HNSCC, cells were incubated with the EGFR inhibitor erlotinib, dasatinib, or a combination of both agents (Fig. 4B). In all cell lines tested, EGFR inhibition did lead to c-Met inactivation with no effect of SFK activation. The combination of erlotinib and dasatinib resulted in a cooperative effect on c-Met activation and a significant decrease in AKT activation in the resistant cell lines. Similarly, our previous work demonstrated that dasatinib and erlotinib are additive in HNSCC cells *in vitro* (9).

**SFK and c-Met inhibitors show synergistic effect on HNSCC cell viability *in vitro* and *in vivo***

Given that c-Met is not inhibited in cell lines that are resistant to SFK inhibition, we hypothesized that persistent c-Met activation may mediate this resistance. To test this, a panel of 7 HNSCC cell lines with diverse sensitivities to SFK inhibition was incubated with dasatinib, PHA665752, or the combination, and cytotoxicity was measured by the MTT assay. We also calculated the combination index for the drug combination (Table 2). A combination index value of less than 1 indicates synergy; a value equal to 1 indicates an additive effect; and a value greater than 1 indicates antagonism. Representative cytotoxicity data are shown in Figure 5A and B.

None of the cell lines demonstrated the extreme sensitivity to PHA-665752 that occurs in cells with amplified c-Met (*IC*₅₀ < 100 nM) (31). However, 3 of the 7 lines demonstrated *IC*₅₀ values that were less than or close to 2.5 μM, a concentration at which we observed significant inhibition of c-Met (Supplementary Fig. 3); inhibition of c-Met was incomplete at a concentration of 1 μM.
As hypothesized, the combination of c-Met and SFK inhibition was synergistic in the dasatinib-resistant cell lines. Consistent with the cytotoxicity data, this finding shows that the combination resulted in significantly more apoptosis than either agent alone (Fig. 5C). Surprisingly, the combination was also synergistic in the dasatinib-sensitive (Tu167, TR146) and intermediate (UMSCC14a) cell lines, suggesting that inhibition of the residual c-Met activation following SFK inhibition was adequate to enhance cytotoxicity (Table 2).

As expected, PHA665752 inhibited c-Met and dasatinib inhibited c-Src in HNSCC cell lines (Fig. 5D). We also examined the effect of these inhibitors on activated ErbB3 because ErbB3 can mediate c-Met’s effects in EGFR inhibitor-resistant non–small cell lung cancer (NSCLC) cell lines (17). However, we did not find any consistent effect of c-Met or SFK inhibition on activated ErbB3. In most of these cell lines, the combination led to decreased signaling through the PI3K pathway (PKD1 or AKT).

Consistent with our in vitro data, we also observed that the combination of c-Src and c-Met inhibition reduced tumor size in vivo (Fig. 5E and Supplementary Fig. 4). In the in vivo studies, we utilized crizotinib due to the poor oral bioavailability of PHA665752. The single agents alone did not significantly affect tumor size. Western blotting of tumors confirmed that the drugs affected their targets (Supplementary Fig. 5). There was a statistically nonsignificant trend toward decreased nodal metastasis in mouse treated with the combination (3 of 20 nodes examined contained tumor, 15%) compared to control (7/28, 25%) or single agents [dasatinib (8/27, 30%) or crizotinib (4/21, 19%)]. The number of mice with nodal metastasis ranged from 42% to 56%.

We previously observed that c-Src inhibition led to a universal inhibition of invasion and migration independent of its effects on apoptosis (10). Both PHA665752 and dasatinib inhibited invasion and migration; the combination was more effective than the single agents (Supplementary Fig. 6). The effect was independent of the effects of either drug on cytotoxicity.

Specific depletion of c-Src and c-Met in HNSCC cell lines

To determine if the enhanced cytotoxic effects of dasatinib and PHA665752 were due to specific effects of the drugs on c-Src and c-Met, respectively, we specifically knocked down c-Src and c-Met with siRNA and measured the surviving cells by using an MTT assay (Fig. 6 and Supplementary Fig. 7). In both Osc-19 and Tu167 cells, c-Src depletion alone led to a decrease of about 25% in cell number, and c-Met depletion alone led to a decrease of about 15% (P < 0.05 vs. control or scrambled siRNA). Consistent with the pharmacologic

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Table 2. Median effects of dasatinib and PHA665752 as single agents and in combination

<table>
<thead>
<tr>
<th>Cell line</th>
<th>Single agent, IC_{50}</th>
<th>Combination, IC_{50}</th>
<th>Combination index simulations</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dasatinib (nM)</td>
<td>PHA665752 (μM)</td>
<td>Dasatinib (nM)</td>
<td>PHA665752 (μM)</td>
</tr>
<tr>
<td>Tu167</td>
<td>45 ± 7.7</td>
<td>6.8 ± 2.1</td>
<td>20 ± 6.6</td>
<td>1.6 ± 0.53</td>
</tr>
<tr>
<td>TR146</td>
<td>67 ± 2.3</td>
<td>2.6 ± 1.0</td>
<td>27 ± 13</td>
<td>0.53 ± 0.27</td>
</tr>
<tr>
<td>UMSCC14a</td>
<td>186 ± 15</td>
<td>1.9 ± 0.7</td>
<td>28 ± 18</td>
<td>0.57 ± 0.37</td>
</tr>
<tr>
<td>Osc19</td>
<td>312 ± 36</td>
<td>8.7 ± 4.9</td>
<td>107 ± 39</td>
<td>1.1 ± 0.39</td>
</tr>
<tr>
<td>Tu167R2</td>
<td>803 ± 189</td>
<td>22 ± 1.4</td>
<td>268 ± 86</td>
<td>1.1 ± 0.34</td>
</tr>
<tr>
<td>Tu167R1</td>
<td>&gt;1000</td>
<td>6.5 ± 2.2</td>
<td>316 ± 129</td>
<td>1.3 ± 0.50</td>
</tr>
<tr>
<td>Tu138</td>
<td>&gt;5000</td>
<td>2.1 ± 0.3</td>
<td>148 ± 19</td>
<td>1.5 ± 0.02</td>
</tr>
</tbody>
</table>

NOTE: Data presented as mean ± SD.
data (Table 2), the results show that the combination was more effective than either of the single siRNAs, with reductions in cell number of 36% for Tu167 and 54% for Osc-19 \((P < 0.05\) vs. control or scrambled or c-Src alone or c-Met alone). As we previously observed \((29)\), the effect of c-Src knockdown was markedly less cytotoxic than SFK inhibition with dasatinib, probably because of 3 factors: dasatinib inhibits all SFKs (not just c-Src), dasatinib is a much more effective c-Src inhibitor than siRNA, and dasatinib likely has off-target effects that contribute to its cytotoxicity \((32)\).

**Discussion**

In this study we sought to identify pathways leading to cytotoxicity downstream of c-Src inhibition and demonstrated that sustained c-Met activation mediates cell survival following c-Src inhibition. We observed a correlation...
Signaling between c-Src and c-Met can be bidirectional. Activation of c-Met by HGF in breast cancer cell lines leads to release of growth factors that activate EGFR, which subsequently activates c-Met in a c-Src–dependent manner. This process is not dependent upon ligand-mediated activation of c-Met, rather the c-Met is activated by c-Src (36). Similarly, c-Met can be activated by EGFR in human hepatoma cell lines (37), anaplastic thyroid cancer cells (38), and lung cancer (39), but the role of c-Src in these systems was not investigated. In a separate study, pharmacologic inhibition of SFKs led to decreased levels of phosphorylated c-Met in 4 of 5 colon cancer cell lines, but the mechanism was not defined (40).

We did not expect there to be only a single mechanism of resistance to c-Src inhibition. This situation is analogous to resistance of cancers to targeted agents and to cytotoxic chemotherapy drugs, which is mediated by diverse mechanisms (33). For example, resistance to EGFR inhibitors in lung cancer can be mediated by additional mutations in EGFR (T790M), amplification of c-Met (17), activation of the insulin growth factor receptor (34), and other undefined mechanisms. Correspondingly, an unbiased approach to identifying proteins with significant changes in tyrosine phosphorylation upon c-Src activation identified 136 proteins with increased tyrosine phosphorylation, including c-Met (35). These data are supported by the finding that gastric cell lines that express c-Met are resistant to SFK inhibition–induced apoptosis (19). We also demonstrated that the reactivation of STAT3 following sustained c-Src inhibition may contribute to resistance to c-Src inhibition (29). Even though alternative mechanisms may exist, however, the combination of c-Met and c-Src inhibitors was synergistic in all cell lines tested, suggesting that this is a rational combination for future clinical studies.
ference in cell type (HNSCC vs. breast) or the different approaches employed to manipulate c-Met activation (i.e., ligand stimulation vs. kinase inhibition). Moreover, c-Met inhibition alone leads to cytotoxicity and Akt inhibition in some cancer cell lines (42) and in HNSCC in vivo (21), but in our HNSCC in vivo, this was not observed.

In lung cancer cell lines, c-Met can mediate resistance to EGFR inhibition. When NSCLC cell lines with activating EGFR mutations were incubated with increasing concentrations of the EGFR inhibitor gefitinib, the resulting gefitinib-resistant NSCLC cells had amplified c-Met and persistent activation of ErbB3 and Akt following exposure to gefitinib. Although these cells were resistant to both gefitinib and PHA665752, the combination resulted in growth inhibition and suppression of Akt and ErbB3 phosphorylation. We also observed suppression of ErbB3 phosphorylation with the combination of dasatinib and PHA665752, but in only 1 of 6 cell lines tested (Tu138). c-Src inhibition had no observed effect on activated EGFR in HNSCC cells (9). EGFR inhibition did lead to c-Met inhibition in resistant cell lines. In NSCLC cell lines, activation of ErbB3 by c-Met was not c-Src dependent (17). Similarly, in breast cancer cell lines, c-Met activation can mediate EGFR resistance, but through a mechanism that is distinct from that of NSCLC. In breast cancer cells, c-Met activation leads to EGFR kinase-independent phosphorylation of EGFR via a c-Src-dependent mechanism. Thus, despite the presence of an EGFR kinase inhibitor, EGFR can still be phosphorylated and contribute to cell growth (43). Interestingly, engagement of EGFR signaling can mediate resistance of NSCLC cells to c-Met inhibition in vitro, further demonstrating an intimate link between these two pathways in lung cancer (44).

Any study using pharmacological agents is limited by drug specificity. Although PHA665752 did drastically reduce the IC50 for dasatinib, it brought this value into a range that we consider SFK specific (<100 nM) in only 2 of the 5 dasatinib-resistant cell lines (Osc-19 and UMSCC14a), suggesting that resistance in these lines may be “driven” by other signaling pathways that may include the JAK-STAT signaling axis (29). However, the enhanced cytotoxicity observed with the combination of c-Src and c-Met siRNA does demonstrate that these 2 specific pathways can cooperate to contribute to cell survival. At the concentrations we used, PHA665752 inhibits c-Met, Ron, Flik-1, and c-Abl (42) and dasatinib inhibits c-Abl, PDGFR, Btk, EphA2, and others (32, 45, 46).

In conclusion, this study offers new insights into the interaction of c-Src and c-Met in HNSCC cells. In cells that were sensitive to SFK inhibition, c-Met was a c-Src substrate and the 2 proteins interacted. This interaction did not occur in resistant cell lines even though the isolated c-Met was a c-Src substrate. This is the first study to demonstrate a potential mechanism by which c-Met activation can mediate resistance to SFK inhibition in only a subpopulation of cancer cells. The synergistic effects of SFK and c-Met inhibition may have important clinical implications for the treatment of HNSCC.

Disclosure of Potential Conflicts of Interest

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