Off-Target Effects of c-MET Inhibitors on Thyroid Cancer Cells

Yan Zhou1,2,4, Conghui Zhao1, Sigal Gery4, Glenn D. Braunstein2, Ryoko Okamoto3, Rocio Alvarez4, Steven A. Miles4, Ngan B. Doan5, Jonathan W. Said5, Jiang Gu1,3, and H. Phillip Koeffler4,6

Abstract

Aberrantly activated c-MET signaling occurs in several cancers, promoting the development of c-MET inhibitors. In this study, we found that eight of eight thyroid cancer cell lines (including six anaplastic thyroid cell lines) have prominent expression of c-MET protein. Fifty percent of the thyroid cancer cell lines (four of eight) were growth inhibited by two small molecule c-MET inhibitors (tivantinib and crizotinib) associated with apoptosis and G2-M cell-cycle arrest. However, crizotinib did not inhibit 50% proliferation of thyroid cancer cells (SW1736 and TL3) at a concentration at which the drug completely inhibited ligand-stimulated c-MET phosphorylation. However, tivantinib was less potent than crizotinib at inhibiting c-MET phosphorylation, but was more potent than crizotinib at decreasing cell growth. Suppressing c-MET protein expression and phosphorylation using siRNA targeting c-MET did not induce cell-cycle arrest and apoptosis. Taken together, tivantinib and crizotinib have off-target(s) activity, contributing to their antitumor activity. In vivo study showed that crizotinib markedly inhibited the growth of thyroid cancer cells (SW1736) in immunodeficient mice. In summary, c-MET inhibitors (tivantinib and crizotinib) suppress the growth of aggressive thyroid cancer cells, and this potential therapeutic benefit results from their non–MET-targeting effects. Mol Cancer Ther; 13(1); 1–10. ©2013 AACR.

Introduction

HGF/c-MET axis plays an essential role in normal physiological processes such as embryonic development, angiogenesis, and wound healing (1). Cancers activate this pathway by several different mechanisms including overexpression of c-MET, or activating mutations of the kinase domain of c-MET. This is associated with activation of downstream signaling pathways including MAPK/ERK, PI3K/AKT, STATs, and IκB/NF-κB, which enhance proliferation, invasion, migration, survival, and metastasis (1, 2).

Various therapeutic approaches to control deregulated c-MET signaling of cancer cells have been developed, including small molecule c-MET kinase inhibitors (3, 4). Tivantinib (ARQ-197) was the first reported non-ATP-competitive small molecule c-MET inhibitor showing a growth-inhibitory effect against a panel of c-MET–expressing cancer cell lines (5). Clinical studies found that it was well tolerated in patients with advanced solid tumors (6, 7). Another drug, crizotinib (PF-2341066), is a potent ATP competitive inhibitor of both c-MET and anaplastic lymphoma kinase (ALK) demonstrating a >100-fold selectivity for inhibition of c-MET compared with >120 other kinases (8). Crizotinib was approved by the U.S. Food and Drug Administration (FDA) for the treatment of patients with ALK positive, non–small cell lung cancer in 2011 (9). Patients are still being recruited for phase I to III antitumor clinical trials for these drugs (http://www.clinicaltrials.gov; 2013).

The most common endocrine malignancy is thyroid cancer whose incidence has been increasing by 5.6% per year in men and 7.0% per year in women since 2005, with an estimated 60,220 new cases expected to be diagnosed in 2013 in the USA (American Cancer Society: Cancer Facts & Figures; 2013). These thyroid cancers are classified as follicular, papillary, medullary, and anaplastic. Individuals with anaplastic thyroid carcinoma (ATC) have a fulminant course with a very poor prognosis (median survival from diagnosis, 5 months; ref. 10).

Both thyroid cancer cell lines and thyroid carcinoma tissue specimens (11–15) have high expression of c-MET. Nearly 70% to 90% of papillary thyroid carcinoma (PTC) samples have c-MET expression as contrasted to undetectable levels in normal thyroid tissue (11–15). To date, only several PTC cell lines (BHP, ref. 16; B-CPAP and TCP-1, ref. 17) were examined and found to be growth inhibited in vitro by an experimental c-MET inhibitor known as PHA665752.
Based on the foregoing data, we examined the effect of 2 c-MET inhibitors (tivantinib and crizotinib) on growth and pathway signaling of 8 human thyroid cell lines, especially focusing on anaplastic thyroid cancer.

Materials and Methods

Compound

c-MET inhibitors tivantinib (ActiveBiochem), crizotinib and SU11274 (Selleck Chemical) were suspended in dimethyl sulfoxide (DMSO) and stored until use in small aliquots at –20°C. Crizotinib used in in vivo experiments was kindly sponsored by Pfizer, Inc. Their molecular structures are showed in Supplementary Fig. S1. Recombinant human HGF (PeproTech) was dissolved in sterile PBS (10 μg/mL), and stored in aliquots at –80°C.

Cell lines and culture

Cancer cell lines used in this study are listed in Table 1. T2 (anaplastic thyroid cancer) and TL3 (lymph node metastasis of T2 anaplastic thyroid cancer) were established in our laboratory (manuscript in preparation) at the beginning of 2010; BHP2-7, WRO, T238, C643, Cal-62, and SW1736 were kindly provided by Dr. James A. Fagin (Memorial Sloan-Kettering Cancer Center, New York) at the end of 2009; the c-MET negative (18) melanoma cell line, MDA-MB-435 was provided by Dr. Guy Juillard (University of California Los Angeles, CA); the breast cancer cell line, MDA-MB-231, and the colon cancer cell line, HT29, were obtained from American Type Culture Collection. The exact receiving dates of MDA-MB-435, MDA-MB-231, and HT29 are not known. SW1736 cells were maintained in RPMI 1640 supplemented with lx MEM nonessential amino acids (Gibco), the other cell lines were maintained in RPMI 1640. Heat-inactivated FBS (10%, v/v; Gemini Bio-Products) was added to all cell cultures. Cells were maintained at 37°C in a humidified chamber of 95% air and 5% CO₂. Cancer cells were passaged using 2.5% trypsin–EDTA solution when reaching 95% confluence. Cell counts were determined using a hemocytometer (Allegiance Healthcare), and only cells in the log phase of growth were used for all studies. All cells were verified by short tandem repeat profiling (UCLA Sequencing & Genotyping Core).

Tissue samples

Normal thyroid tissue samples were obtained from the National University Hospital-National University of Singapore (NUH-NUS) Tissue Repository with approval of the Institutional Review Board (IRB) of NUH-NUS for research use. Five adjacent noncancerous thyroid tissues were obtained from surgical specimens and they were used as normal thyroid control tissue. Three papillary thyroid carcinoma tissues from surgical specimens were obtained from Department of Pathology, UCLA Medical Center, Los Angeles, CA, and the use was approved by UCLA IRB.

Western blotting

Cell lysates were prepared using the lysis buffer [50 mmol/L Tris-HCl (pH 7.4), 150 mmol/L NaCl, 0.5% NP-40] containing both protease and phosphatase inhibitor cocktail (Roche Molecular Biochemicals). Protein lysates (50 μg) were boiled in Laemmli sample buffer (Bio-Rad Laboratories), separated by electrophoresis on precast 4% to 15% SDS-polyacrylamide gels (Bio-Rad), and transferred to polyvinylidene difluoride membranes. Membranes were probed with antibodies from Cell Signaling Technology as well as Santa Cruz Biotechnology, and developed using the enhanced chemiluminescence kit (Pierce). Western blots were stripped between hybridizations with stripping buffer [10 mmol/L Tris-HCl (pH 2.3), 150 mmol/L NaCl]. All antibodies used in this study are listed in Supplementary Table S1.

RNA interference

c-MET siRNA_5 (S100300860) and c-MET siRNA_10 (S102654897) were purchased from Qiagen. The c-MET siRNAs and a control scramble siRNA (Ambion) were

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Reported mutation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW1736</td>
<td>ATC</td>
<td>BRAF V600E</td>
<td>(26)</td>
</tr>
<tr>
<td>Cal-62</td>
<td>ATC</td>
<td>KRAS G12R</td>
<td>(26)</td>
</tr>
<tr>
<td>T238</td>
<td>ATC</td>
<td>PIK3CA E542K and BRAF V600E</td>
<td>(26)</td>
</tr>
<tr>
<td>T2</td>
<td>ATC</td>
<td>None</td>
<td>a</td>
</tr>
<tr>
<td>TL3</td>
<td>ATC</td>
<td>P53 C277Y</td>
<td>a</td>
</tr>
<tr>
<td>C643</td>
<td>ATC</td>
<td>HRAS G13R</td>
<td>(26)</td>
</tr>
<tr>
<td>BHP2-7</td>
<td>PTC</td>
<td>RET/PTC rearrangement</td>
<td>(27)</td>
</tr>
<tr>
<td>WRO</td>
<td>FTC</td>
<td>BRAF WT</td>
<td>(27)</td>
</tr>
<tr>
<td>MDA-MB-435</td>
<td>Melanoma</td>
<td>BRAF V600E</td>
<td>(28)</td>
</tr>
<tr>
<td>MDA-MB-231</td>
<td>Breast Cancer</td>
<td>BRAF G464V and KRAS G13D</td>
<td>(28)</td>
</tr>
<tr>
<td>HT29</td>
<td>Colon Cancer</td>
<td>P53 R273H</td>
<td>(29)</td>
</tr>
</tbody>
</table>

aOur unpublished data. T2 is the primary ATC and TL3 is the lymph node metastasis of T2.
transfected into SW1736 cells using Lipofectamine 2000 (Invitrogen) according to the manufacturer’s instructions.

**Cellular proliferation assay**

For measurement of proliferation, cells were plated into 96-well plates intriplicates and treated with either diluent control (DMSO, 0.1%) or various concentrations of either tivantinib or crizotinib (0.03–10 μmol/L). The cells were incubated at 37°C for 72 hours, at which time 10 μL MTT (5 mg/mL; Sigma), dissolved in PBS, was added to each well, followed 4 hours later by 100 μL of 20% SDS. The absorbance of the product was measured with an ELISA reader at 540 nm after 16 additional hours. The half maximal inhibitory concentration (IC50) represented the concentration, which reduced 50% cellular growth compared with diluent control wells.

**Cell-cycle analysis and apoptosis assay**

For cell-cycle analysis, cells were cultured with various concentrations of test compounds for 24 hours, washed, fixed in 70% ethanol, treated with RNase A, and exposed to propidium iodide for analysis by flow cytometry. For apoptosis assay, Annexin V-FITC Apoptosis Detection Kit (BD Pharmingen) was used according to the manufacturer’s instructions.

**Reverse transcription and quantitative real-time PCR**

Total RNA from cultured cells was extracted using RNase-Free DNase set (Qiagen); RNA (1 μg) was processed directly to cDNA by reverse transcription with iScript cDNA Synthesis Kit (Bio-Rad) following the manufacturer’s instructions. Real-time PCR was performed to evaluate mRNA level of c-MET in thyroid cancer cells and normal tissues using SsoFast EvaGreen Supermix (Bio-Rad). Each sample was tested in triplicates, and GAPDH processed directly to cDNA by reverse transcription with iScript cDNA Synthesis Kit (Bio-Rad). Each sample was tested in triplicates, and GAPDH was used as a control for the target gene. Primers used: c-MET forward: AGTGAAGTGGATGGCTTTGG; c-MET reverse: GGCAATGTTCCGGTGTTAGG; GAPDH forward: GTCAGGCTAGAACCAGGAA; GAPDH reverse: AAATGAGCCCCAGCCTTCTC.

**Murine xenograft model**

Female n/nu athymic mice (5-week-old) were purchased from Vital River Laboratory Animal Technology and maintained in pathogen-free conditions. Both the crizotinib group and the vehicle (water) group included 5 mice. A total of 1.2 × 10⁷ SW1736 cells in 0.2 mL Matrigel (BD Biosciences) were injected subcutaneously in both hind-flanks of the nude mice. Daily treatment with either 50 mg/kg crizotinib or vehicle by oral gavage began 10 days after injection when the tumors were established. Tumors were measured with Vernier calipers every 3 to 4 days, and the volume was calculated using the formula: (length × width × depth) × 0.5236 (19). The animal experiment was performed in accordance with the guideline of Cedars-Sinai Research Institute. Results were expressed as mean tumor volume ± SD. Mice were humanely euthanized on day 50, 4 hours after crizotinib or vehicle was gavaged. The tumors were dissected, and either fixed in 10% formalin followed by paraffin embedding for immunohistochemistry, or rapidly frozen in liquid nitrogen followed by homogenizing on ice for Western blotting.

**Immunohistochemistry**

Paraffin-embedded tissue sections were deparaffinized and immersed in 3% hydrogen peroxide to eliminate endogenous peroxidase activity. To assess cellular proliferation, primary antibodies to Ki67 were used. Following over-night primary antibody incubation, the sections were rinsed then incubated with a secondary antibody labeled with peroxidase at 37°C for 20 minutes, and colorized with the enzyme substrate 3-amino-9-ethylcarbazole (Dako). Following every step, sections were rinsed with 0.01M PBS 3 times for 5 minutes each. Slides were lightly counterstained with hematoxylin. PBS was used to replace the primary antibody to serve as a negative control.

**Statistical analysis**

Student t test was used for all the statistical analyses, and significant differences were considered as P < 0.05.

**Results**

**Expression of c-MET in thyroid cancer cells**

A melanoma control cell line MDA-MB-435 (Fig. 1A) had little detectable c-MET protein by Western blotting, although all 8 thyroid cancer cell lines, including 1 follicular thyroid carcinoma (FTC) cell line (WRO), 1 PTC cell line (BHP2-7), and 6 ATC cell lines (SW1736, Cal-62, T238, T2, TL3, C643), showed notable expression of the c-MET protein (Fig. 1A), with 4 of 8 thyroid cancer cell lines (T2, WRO, BHP2-7, T238) having clear constitutively phosphorylated c-MET (Fig. 1A). Each had a dramatic increase of their phosphorylated c-MET receptor after 10 minutes exposure to 20 ng/mL HGF, a c-MET ligand (Fig. 1A). Normal thyroids (5 samples; Fig. 1B) demonstrated no detectable c-MET; and PTC tissues (3 samples; Fig. 1B) showed detectable c-MET expression, which was markedly less than the T2 cell line. Generally, levels of c-MET mRNA in PTC tissues were higher than normal thyroid tissues (Fig. 1C). However, levels of c-MET mRNA in the thyroid cancer cell lines were lower than the normal thyroid tissues and PTC tissues (Fig. 1C), suggesting differences in posttranscriptional control of this tyrosine kinase receptor between the thyroid cancer cell lines and resected thyroid tissue/carcinoma.

**Effect of c-MET inhibitors on cancer cell proliferation**

Proliferation of 4 of 8 thyroid cancer cell lines (SW1736, T2, TL3, BHP2-7) was inhibited by c-MET inhibitors, with an IC50 between 0.1 and 1 μmol/L for tivantinib (Fig. 2A) and 2 to 3.5 μmol/L for crizotinib (Fig. 2B). The other 4 thyroid cancer cell lines (Cal-62, T238, WRO, C643), as well as the c-MET negative MDA-MB-435 melanoma cells,
had minimal response to either tivantinib or crizotinib, not reaching an IC_{50} value even in the presence of the maximal drug dose (10 \text{ mmol/L}).

The ability of tivantinib and crizotinib to inhibit cell growth of 2 nonthyroid c-MET–expressing cell lines (MDA-MB-231, breast cancer; HT29, colon cancer) was also tested. For tivantinib, the IC_{50} to inhibit cell proliferation of MDA-MB-231 and HT29 was 0.65 and 0.54 \text{ mmol/L}, respectively (Supplementary Fig. S2A). For crizotinib, the IC_{50} for the inhibition of cell proliferation was 2.8 \text{ mmol/L} for MDA-MB-231 and 2.6 \text{ mmol/L} for HT29 (Supplementary Fig. S2A).

**Effect of c-MET inhibitors on cell cycle and apoptosis of human thyroid cancer cells**

Three ATC cell lines (SW1736, T2, and TL3) that were responsive to the c-MET inhibitors were analyzed for changes in cell cycle and apoptosis after exposure to increasing doses of either tivantinib or crizotinib (0.1–10 \text{ mmol/L}). Both agents induced a profound dose-dependent cell growth arrest in the G2–M phase for each of the cell lines (Fig. 3A, B). For example, a 24-hour exposure of either tivantinib (1 \text{ mmol/L}) or crizotinib (10 \text{ mmol/L}) induced a mean G2–M arrest of 57% and 74%, respectively, of the SW1736 cells, compared with 9% for the diluent-treated control cells. Similar dose–response curves were noted for T2 (G2–M: 45%, and 26% cells when treated with either 1 \text{ mmol/L} tivantinib or 10 \text{ mmol/L} crizotinib, respectively, compared with 3% cells in control dishes) and for TL3 (G2–M 23% and 48% treated with either 1 \text{ mmol/L} tivantinib or 10 \text{ mmol/L} crizotinib, respectively, compared with 2% of cells receiving diluent control; Fig. 3B).

Cell-cycle analysis revealed that these inhibitors induced apoptosis (Fig. 3A, sub-G1 cells). To investigate more thoroughly, the cells were analyzed for Annexin V/propidium iodide positivity after exposure to either tivantinib or crizotinib (0.1, 1.0, and 10 \text{ mmol/L}, 24 hours; Fig. 3C). When cultured with 10 \text{ mmol/L} of either tivantinib or crizotinib, apoptosis was respectively: 14% and 15% for SW1736, 21% and 19% for T2, and 20% and 27% for the TL3 thyroid cancer cells. In contrast, apoptosis was 10% (SW1736), 11% (T2), and 10% (TL3) for diluent-treated control cells under the same conditions (Fig. 3C).

**c-MET inhibitors block HGF-induced activation of c-MET and its downstream signaling**

Two thyroid cancer cell lines (SW1736 and TL3 cells), who were growth inhibited by both c-MET inhibitors, were
serum-starved (24 hours) followed by 10 minutes stimulation with 20 ng/mL HGF. P-MET increased dramatically after HGF stimulation in both cells; tivantinib and crizotinib (0.1, 1.0, and 10 μmol/L) in a dose-dependent manner inhibited this induced phosphorylation (Fig. 4). Furthermore, phosphorylation of AKT and STAT3 was attenuated in both cells in a dose-dependent manner, mirroring an inactivation of c-MET. Similarly, SU11274 (another ATP-competitive c-MET inhibitor, 10 μmol/L) also inhibited P-MET, P-AKT, and P-STAT3 in both cells. Phosphorylation of ERK and 4E-BP1 (indicator of the activation of mTOR pathways) was not significantly altered by either inhibitor (Fig. 4). Crizotinib was 10- to 100-fold more potent than tivantinib in blocking c-MET phosphorylation (Fig. 4 and Table 2). In contrast, both inhibitors potently decreased levels of P-STAT3 and P-AKT (Fig. 4).

Tivantinib and crizotinib also inhibited HGF-induced c-MET phosphorylation of MDA-MB-231 and HT29 in a dose-dependent manner (Supplementary Fig. S2B). Crizotinib was nearly 100-fold more potent in preventing phosphorylation of c-MET after HGF stimulation (Supplementary Fig. S2B).

Crizotinib markedly decreased growth of SW1736 anaplastic thyroid cancer cell xenografts in vivo

To test if crizotinib could suppress thyroid cancer cell growth in vivo, nude mice were subcutaneously implanted with SW1736 human anaplastic thyroid tumor cells. Ten days after implantation, mice were given crizotinib [50 mg/kg or vehicle (water) daily by oral gavage]. The experiment was stopped at day 50, because of the excessive tumor size of the vehicle cohort of mice. Crizotinib markedly suppressed SW1736 cell growth in the xenograft model (Fig. 5A). At the end of the experiment, the mean tumor volume was 2.26 ± 0.72 cm3 in the vehicle group, compared with 1.00 ± 0.36 cm3 in the crizotinib cohort (55.8% decrease; Fig. 5A). Compared with vehicle-treated nude mice, SW1736 cancer cells obtained from crizotinib-treated mice showed less c-MET phosphorylation (Fig. 5B) and Ki67 positivity (arrows; Fig. 5C).

Downregulation of c-MET in SW1736 did not induce cell-cycle arrest or apoptosis

SW1736 thyroid cancer cells were transfected with siRNAs that directly targeted c-MET, and both c-MET protein expression and phosphorylation were suppressed markedly after 48 hours (Fig. 6A). Neither cell-cycle arrest nor apoptosis was observed in SW1736 cells at 48 hours after c-MET siRNA transfection (Figs. 6B and C). For example, the percent of cells in the G2-M phase was 8.7%, 9.5%, and 8.3% (Fig. 6B), and the apoptosis values were 9.7%, 10.2%, and 10.5% (Fig. 6C) after the cells were transfected with either control siRNA, c-MET siRNA_5, or
Discussion

In our study, c-MET protein was predominantly expressed in 8 of 8 thyroid cancer cell lines, weakly expressed in 3 PTC tissues and undetectable in 5 normal thyroids and a melanoma cell line (MDA-MB-435; Figs. 1A and B). The reason that the expression level of c-MET protein is lower in PTC tissue samples than the PTC (and other) cell lines using Western blotting might be as bellow: cell lines are pure populations of c-MET positive cells, whereas the resected PTC tissues may contain noncancerous cells that are c-MET negative, such as cells in the peritumoral normal follicle (20), causing the average c-MET level in the tissue to be lower. In parallel with this observation, several reports performed immunoprecipitation to enrich c-MET protein before detecting its expression using Western blotting in PTC tissue samples (11, 21). We did find that levels of c-MET mRNA in PTC tissues were 4 to 7 folds higher than present in normal thyroids (Fig. 1C), consistent with a previous report, indicating that c-MET mRNA levels were 6.6-fold higher in PTC tissues compared with paired normal thyroid tissues (22). In contrast to the levels of c-MET protein, we noted levels of c-MET mRNA were comparable in all the thyroid cancer cell lines (including a PTC cell line, BHP2-7) and the normal thyroid tissues but notably lower than in the PTC samples (Fig. 1C). Further studies are needed to determine if posttranscriptional regulation of levels of c-MET protein has an important role in thyroid tissues.

Our second observation concerned the antiproliferative activity of the 2 c-MET inhibitors: tivantinib, a non-

---

**Figure 3.** Effect of tivantinib and crizotinib on cell cycle and apoptosis. A, cell-cycle analysis of SW1737, T2, and TL3 thyroid cancer cell lines after treatment with increasing concentrations of tivantinib and crizotinib (0.1, 1.0, and 10 μmol/L, 24 hours). B, graphic display of G2–M data shown in A. C, apoptosis measurement (% Annexin V-positive cells) after these cells were treated with either tivantinib or crizotinib (0.1, 1.0, and 10 μmol/L, 24 hours). Results expressed as mean ± SD. *, P < 0.05; **, P < 0.01.

c-MET siRNA_10, respectively, and no statistical significant difference was observed.
ATP-competitive inhibitor, and crizotinib, an ATP-competitive inhibitor. Crizotinib completely inhibited c-MET phosphorylation in SW1736 and TL3 thyroid cancer cells at 1 and 0.1 μmol/L (Fig. 4 and Table 2), respectively. Nevertheless, crizotinib inhibited less than 50% of SW1736 cell growth at 1 μmol/L (Fig. 2B), and less than 20% of TL3 cell growth at 0.1 μmol/L (Fig. 2B). The inconsistency between the concentrations required for inhibiting c-MET phosphorylation and those impairing cell proliferation clearly indicates that c-MET was not the sole target of crizotinib causing a growth inhibition of the thyroid cancer cell growth.

However, tivantinib was at least 10-fold less potent than crizotinib at attenuating phosphorylation of c-MET and AKT (Fig. 4 and Table 2); however, tivantinib was 5- to 10-fold more potent than crizotinib in inhibiting cell growth (Fig. 2 and Table 2), as well as mediating apoptosis and G0–M cell-cycle arrest (Fig. 3). Congruent with these biological findings, biochemical analysis showed that crizotinib and tivantinib inhibited c-MET with a Ki value of 4 nmol/L (8) and 355 nmol/L (5), respectively. The observation that tivantinib more potently inhibited growth of SW1736 and TL3 than crizotinib, but crizotinib more potently inhibited c-MET activation, indicates that tivantinib also impaired thyroid cancer cell proliferation in a non-MET-targeting manner.

Two nonthyroidal cancer cell lines (MDA-MB-231 and colon cancer cell HT29) have been tested in previous studies (5, 8) using c-MET inhibitors. In these 2 cell lines, we again noticed the disassociation between the ability of the drugs (tivantinib and crizotinib) to inhibit the c-MET activation and to impair cell growth: (i) crizotinib did not markedly inhibit cell growth when c-MET phosphorylation was greatly suppressed (Supplementary Fig. S2); and (ii) tivantinib showed a more potent capability in suppressing cell growth, although it is a weaker c-MET inhibitor comparing to crizotinib (Supplementary Fig. S2 and Table 2). Hence, both tivantinib and crizotinib potently inhibit thyroid cancer cells, probably in part by non-MET signaling pathways.

To explore further, the question of how important c-MET inhibition is as a potential therapeutic target for thyroid cancer cells, we silenced c-MET in thyroid cancer cells (SW1736). Inhibition of c-MET phosphorylation and protein levels of c-MET in SW1736 cells (Fig. 6A) did not

Table 2. Tivantinib and crizotinib inhibition (IC_{50}) of p-MET and cell growth of cancer cells

<table>
<thead>
<tr>
<th></th>
<th>Tivantinib</th>
<th>Crizotinib</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p-MET inhibition (IC_{50})</td>
<td>Growth inhibition (IC_{50})</td>
</tr>
<tr>
<td>MDA-MB-231</td>
<td>Report (5, 8)</td>
<td>0.1–0.3 μmol/L</td>
</tr>
<tr>
<td></td>
<td>Test</td>
<td>&gt; 1 μmol/L</td>
</tr>
<tr>
<td>HT-29</td>
<td>Report (5, 8)</td>
<td>0.1–0.3 μmol/L</td>
</tr>
<tr>
<td></td>
<td>Test</td>
<td>&gt; 1 μmol/L</td>
</tr>
<tr>
<td>SW1736</td>
<td>Test</td>
<td>≈ 1 μmol/L</td>
</tr>
<tr>
<td>TL3</td>
<td>Test</td>
<td>≈ 1 μmol/L</td>
</tr>
</tbody>
</table>

NOTE: IC_{50} values of p-MET inhibition in our tests were estimated according to the Western blotting results. Abbreviation: NA, not analyzed.
produce either notable cell-cycle arrest (Fig. 6B) or apoptosis (Fig. 6C). This is further evidence indicating that the non-MET off-target activity of both inhibitors mainly contributed to their observed cytotoxic effects on thyroid cancer cells.

Furthermore, Basilico and colleagues (23) and Katayama and colleagues (24) reported that the cytotoxic activity of tivantinib against cancer cells is because of perturbating cellular microtubule dynamics. This is consistent with our finding that tivantinib has unidentified off-target antitumor activity independent of c-MET. However, in contrast to prior knowledge (5), both research groups reported that tivantinib does not suppress c-MET phosphorylation in tumor cells. We find that tivantinib only weakly suppressed c-MET phosphorylation; this discrepancy between the studies may represent genomic or tissue specific differences between the cancer cells.

Crizotinib was initially reported as a c-MET inhibitor (8). According to its FDA review document (25), crizotinib showed inhibitory activity in the nmol/L range against 17 kinases (c-MET, Tie2, TrkA, ALK, TrkB, Abl, Yes, Lck, Rse, Axl, Fes, Lyn, Arg, Ron, Abl, Mer), and produced a 50% cellular inhibitory activity of less than 2.8 μmol/L for 9 kinases (c-MET, Tie2, TrkA, ALK,
TrkB, Lck, Axl, Ron, Abl). Although c-MET is not the main functional target of crizotinib in thyroid cancer cells, it still suppressed thyroid cancer cell growth both in vitro (Figs. 2 and 3) and in vivo (Figs. 6A, B, and D), indicating its potential benefit in thyroid cancer therapy, especially anaplastic thyroid cancer therapy.

Crizotinib and tivantinib are currently in clinical trials (http://www.clinicaltrials.gov; 2013). Our studies suggest that they may have a benefit for therapy of thyroid cancer, probably as a result of their non-MET targeting effect(s). An expanded understanding of these additional signaling pathways may allow monitoring of the tumor cells before and after initiation of treatment to choose the best drug therapy.

Disclosure of Potential Conflicts of Interest
No potential conflicts of interest were disclosed.

Authors’ Contributions
Conception and design: Y. Zhou, S. Gery, G.D. Braunstein, J. Gu, H.P. Koeffler
Acquisition of data (provided animals, acquired and managed patients, provided facilities, etc.): Y. Zhou, C. Zhao, R. Okamoto, N.B. Doan, J.W. Said, H.P. Koeffler
Analysis and interpretation of data (e.g., statistical analysis, biostatistics, computational analysis): Y. Zhou, C. Zhao, R. Okamoto, J.W. Said, H. P. Koeffler
Writing, review, and/or revision of the manuscript: Y. Zhou, S. Gery, G.D. Braunstein, S. Miles, J. Gu, H.P. Koeffler
Administrative, technical, or material support (i.e., reporting or organizing data, constructing databases): C. Zhao, G.D. Braunstein, R. Okamoto
Study supervision: S. Miles

Acknowledgments
The authors thank Drs. Q. Cao, D. Yin, D. Hyun Lee, D. Lin, D. Chan, M. Koren-Michowitz, and M. Garg for their helpful discussions.

Grant Support
This study was supported by The Cedars-Sinai Thyroid Cancer Program, National Institutes of Health grant 5R01CA026038-33, and the Singapore Ministry of Health’s National Medical Research Council under its Singapore Translational Research (STaR) Investigator Award to H.P. Koeffler, H. and C. Koeffler Funds, China Scholarship Council, and National Natural Science Foundation of China grants 81030033 and 30971150 to J. Gu.

The costs of publication of this article were defrayed in part by the payment of page charges. This article must therefore be hereby marked advertisement in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.

Received March 19, 2013; revised October 10, 2013; accepted October 21, 2013; published OnlineFirst October 29, 2013.

References


Molecular Cancer Therapeutics

Off-Target Effects of c-MET Inhibitors on Thyroid Cancer Cells

Yan Zhou, Conghui Zhao, Sigal Gery, et al.

Mol Cancer Ther  Published OnlineFirst October 29, 2013.

Updated version
Access the most recent version of this article at:
doi:10.1158/1535-7163.MCT-13-0187

Supplementary Material
Access the most recent supplemental material at:
http://mct.aacrjournals.org/content/suppl/2013/10/29/1535-7163.MCT-13-0187.DC1

E-mail alerts
Sign up to receive free email-alerts related to this article or journal.

Reprints and Subscriptions
To order reprints of this article or to subscribe to the journal, contact the AACR Publications Department at pubs@aacr.org.

Permissions
To request permission to re-use all or part of this article, contact the AACR Publications Department at permissions@aacr.org.