MET exon 14 deletion (METex14): finally, a frequent-enough actionable oncogenic driver mutation in non-small cell lung cancer to lead MET inhibitors out of “40 years of wilderness” and into a clear path of regulatory approval

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The hepatocyte growth factor (HGF) ligand and its receptor MET (mesenchymal-epithelial transition) tyrosine kinase receptor axis has long been demonstrated to be important in oncogenesis and metastasis in multiple tumor types. Mechanisms of dysregulation of the HGF-MET axis includes over-expression of the HGF ligand, activating point mutations in MET, MET gene amplification, MET protein over-expression and potentially MET rearrangements. Many structural different MET tyrosine kinase inhibitors (TKIs) have been developed to target the HGF-MET axis pathway but so far the results have been disappointing (1).

In non-small cell lung cancer (NSCLC), MET amplification has been shown to be an actionable driver mutation as high level of de novo MET amplification (MET/CEP7 >5) was effectively inhibited by crizotinib, an ALK/ROS1/MET TKI (2,3). However, the incidence of true MET amplification and not the broad category of MET polysomy (copy numbers gain without respect to other gene copy number gained simultaneously) is rather rare accounting for about 1% of all NSCLC (3). Secondary acquired MET amplification constitutes about 5% of resistance mechanism to first- or second-generation epidermal growth factor receptor (EGFR) TKI in NSCLC patients harboring activating EGFR mutations (4,5). Thus the incidence of de novo or secondary MET amplification is low as compare to EGFR T790M which accounts for approximately 60% of the resistance mechanism. Additionally, the combination of MET TKI and EGFR TKI trials in NSCLC patients have been disappointing so far. For examples, the combination of crizotinib (MET TKI) and erlotinib (EGFR TKI) was not able to reach the approved dose of each approved agent due to toxicities of the combination (6). Additionally, the increased interstitial lung disease (ILD) observed with the combination of tivantinib and erlotinib as compared to erlotinib alone led to an early termination of a randomized phase 3 trial (ATTENTION) in Asia (7). Furthermore, the failure of the addition of tivantinib to erlotinib to improved overall survival as compared to erlotinib alone in a molecularly unselected nonsquamous NSCLC patients from a randomized phase 3 trial (MARQUEE) involving more than 1,000 patients is the latest blow to MET TKIs in gaining regulatory approval to enter clinical care (8). Given the relative low frequency of MET amplification as a resistance mechanism, clinical trials investigating combination of EGFR and MET TKIs in EGFR-positive NSCLC patients will take time to mature with no guarantee of success (e.g., ClinicalTrials.gov number: NCT01610336). Point mutations have been described throughout the MET gene but none of the mutations are directly activating I NSCLC to date (with the exception of Y1003N which will be discussed later) (1). More recently KIF5B-MET
fusion have been described in NSCLC by next generation sequencing (9). While the KIF5B-MET rearrangement is likely to be an activating genetic alteration in NSCLC similarly to ALK and ROS1 rearrangement in NSCLC, the frequency is likely very low and to date there is no report in the literature of any NSCLC patients harboring MET rearrangement responding to MET inhibitors.

Another alteration in MET that is potentially actionable in NSCLC is MET exon 14 deletion (METex14) mutations resulting in defective messenger RNA (mRNA) splicing due to mutations/deletions at the splice donor or acceptor sites around or involving MET exon 14. Initially reported in both small cell lung in 2003 and then in NSCLC in 2005 (10,11), the significance of these splice site mutations/deletions were demonstrated in 2006 by Kong-Beltran and colleagues where multiple point mutations and deletions in the splice donor and acceptor sites resulted in the exon 14 of MET gene being spliced out of the eventual mature MET mRNA (12).

MET exon 14 contains the Cbl ubiquitin ligases site on tyrosine residue 1003 (Y1003) where ubiquitin is attached to the tyrosine residue and led to the lysosomal degradation of the MET protein (13). Hence, missense mutation of Y1003 residue or “skipping” of the protein region that is encoded by MET exon 14 results in MET protein to in a relative over-expression of MET protein and enhanced MET activation and subsequent oncogenesis. The findings of METex14 by Ma and colleagues and Kong-Beltran and colleagues were subsequently confirmed by whole genome sequencing (14,15) and estimated to be around 3–4% of adenocarcinoma from The Cancer Genome Atlas (TCGA) project (15). Interestingly, TCGA discovered that some of MET splice site mutations resulted in incomplete splicing so a low level of the normal size MET protein is expressed. Whether “incomplete” MET splicing is as oncogenic remain to be determined its existence provides evidence that in order to develop companion diagnostic tests for future clinical use, and quantitative RNA approach will more accurately reflect the biological situation of the tumor environment with corresponding MET protein expression as quantified by immunohistochemistry (IHC) is also.

While there have been ample pre-clinical evidence pointing to the significance of METex14, the clinical evidence was lacking until Paik and colleagues demonstrated these mutations are actionable and inhibition by MET TKIs can result in clinical benefit in NSCLC patients harboring these MET exon 14 alterations (16). In the 2015 Cancer Discovery paper, Paik and colleagues first confirmed the existence of METex14 is about 4% of adenocarcinoma of the lung similar to what was observed the TCGA, a substantial portion of a potential driver mutation according to the thoracic oncology community. Of the 8 (out of 178 adenocarcinoma samples) adenocarcinoma of lung patients with MET exon 14 mutation, 7 harbored splice site mutations while 1 with Y1003 mutation. Of note of the 6 samples that MET protein expression could be tested, all 6 had 3+ IHC score (H-score of 300) indicating high MET protein expression. Importantly, in 6 out of the 8 samples MET was not amplified while one had intermediate level of amplification (MET/CEP7 =3.8) and one had high level of amplification (MET/CEP7 =6.0) indicating MET exon 14 mutations and de novo wildtype MET amplification is likely to be mutually exclusive. Frampton and colleagues, in an accompanying paper in the same issue of Cancer Discovery as Paik and colleagues, did identify that MET amplification (likely of the allele with the MET exon 14 mutations and not the wildtype MET gene) was associated with METex14 (17).

Importantly Frampton and colleagues survey > 38,000 clinical tumor samples submitted to Foundation Medicine Inc. and subject to hybrid-capture next generation sequencing and found that lung cancer by far is the tumor type that harbors MET exon 14 mutations. Approximately 3% of adenocarcinoma of the lung and 2.3% of non-adenocarcinoma of lung cancer harbored MET exon 14 mutations that will likely result in METex14. At the same time, Halmos and colleagues reported that METex14s occurred up to 22% of pulmonary sarcomatoid carcinoma (18) although this high frequency of METex14 needed to be independently verified from different tumor banks.

Of the 8 patients with MET exon 14 mutations described by Paik and colleagues (16), 4 received anti-MET therapy and 3 out of the 4 patients had a response (Table 1). Contemporaneously, other investigators have also published case reports alone or embedded in larger surveys of METex14 in solid tumors (Table 1). First, all histologies of NSCLC were found to harbor METex14 (adenocarcinoma, squamous cell, large cell, and sarcomatoid). Second, both never-smokers and ever-smokers harbored METex14. Third, in all cases with the exception of one where IHC were performed MET protein expression is high (3+) thus providing evidence that MET protein is not degraded at the normal rate as expected. Fourth, three different MET TKIs have been shown single agent activity against METex14 with durable partial response. In summary, given the confluence of the relative high incidence (3–4%) of METex14 among major histologies of lung cancer reported by large clinical database from commercial diagnostic company, single
institutions, and the TCGA together with case reports/series of the significant preliminary single agent activity of MET TKIs against METex14, suddenly the “holy grail” of eventually getting a MET TKI approved for clinical use in NSCLC is suddenly thrust upon us. Clinical trials involving MET inhibitor are now investigating their activities against MET inhibitors. For example, the on-going phase 1/2 crizotinib trial has already produced ground-breaking results in ALK-rearranged and ROS1-rearranged NSCLC is enrolling NSCLC METex14 patients (ClinicalTrials.gov number: NCT00585195) (23,24). Besides completing clinical trials with MET TKIs in NSCLC METex14 patients as soon as possible, several concurrent projects in MET exon14 deletions needed to be completed also. First, the clinicopathologic characteristics of these NSCLC METex14 patients remained limited and elusive (Table 1). Hence survey of large databases to fully characterize these METex14 NSCLC patients is urgently needed to help guide future screening and identification of these patients. Second, the development of a companion diagnostic(s) to accompany the regulatory approval of MET TKIs is urgently needed. Given the TCGA identified “incomplete skipping”, any RNA based detected method is probably preferable although the mutations in the DNA level underlying the METex14 is diverse as demonstrated by Frampton and colleagues with implication of basic science research for years to come. Finally, although not detected by Frampton and colleagues, Lee and Colleagues in Korea (25) have detected comparable

Table 1 List of NSCLC patients with METex14 responded to MET tyrosine kinase inhibitors

<table>
<thead>
<tr>
<th>Number</th>
<th>Age/gender</th>
<th>Smoking status</th>
<th>Histology</th>
<th>MET exon 14 alterations</th>
<th>MET IHC</th>
<th>MET amplification</th>
<th>Best (duration of) response</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80/F</td>
<td>NS</td>
<td>Adeno</td>
<td>Splice donor site mutation</td>
<td>3+</td>
<td>Yes</td>
<td>CR (&gt;7 months) (PERIST) to cabozantinib</td>
<td>Paik et al., Cancer Dis 2015 (16)</td>
</tr>
<tr>
<td>2</td>
<td>78/M</td>
<td>ES</td>
<td>Adeno</td>
<td>Splice donor site deletion</td>
<td>3+</td>
<td>NR</td>
<td>PR to crizotinib (lung); PD to crizotinib (liver)</td>
<td>Paik et al., Cancer Dis 2015 (16)</td>
</tr>
<tr>
<td>3</td>
<td>65/M</td>
<td>ES</td>
<td>Adeno</td>
<td>Splice donor site mutation</td>
<td>NR</td>
<td>NR</td>
<td>PR (&gt;7 months) to crizotinib</td>
<td>Paik et al., Cancer Dis 2015 (16)</td>
</tr>
<tr>
<td>4</td>
<td>90/F</td>
<td>NS</td>
<td>Adeno</td>
<td>Splice donor site mutation</td>
<td>NR</td>
<td>NR</td>
<td>PR (&gt;5 months) to crizotinib</td>
<td>Paik et al., Cancer Dis 2015 (16)</td>
</tr>
<tr>
<td>5</td>
<td>86/M</td>
<td>NS</td>
<td>Adeno</td>
<td>Splice donor site deletion</td>
<td>2+</td>
<td>NR</td>
<td>PR (5 weeks) to crizotinib</td>
<td>Jenkins et al., Clin Lung Cancer 2015 (19)</td>
</tr>
<tr>
<td>6</td>
<td>71/M</td>
<td>ES</td>
<td>Adeno</td>
<td>Splice donor site mutation “D1028H”</td>
<td>NR</td>
<td>No</td>
<td>PR (&gt;6 months) to crizotinib</td>
<td>Waqar et al., J Thorac Oncol 2015 (20)</td>
</tr>
<tr>
<td>7</td>
<td>76/F</td>
<td>ES</td>
<td>Adeno</td>
<td>Splice donor site mutation “D1010H”</td>
<td>NR</td>
<td>No</td>
<td>PR (&gt;8 months) to crizotinib</td>
<td>Mendenhall et al., J Thorac Oncol 2015 (21)</td>
</tr>
<tr>
<td>8</td>
<td>82/F</td>
<td>Large cell</td>
<td>Splice donor site mutation</td>
<td>3+</td>
<td>Yes*</td>
<td>PR (&gt;5 months) to capmatinib</td>
<td>Frampton et al., Cancer Dis 2015 (17)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>66/F</td>
<td>ES</td>
<td>SqCC</td>
<td>Splice donor site mutation</td>
<td>3+</td>
<td>NR</td>
<td>PR (&gt;13 months) to capmatinib</td>
<td>Frampton et al., Cancer Dis 2015 (17)</td>
</tr>
<tr>
<td>10</td>
<td>74/F</td>
<td>ES</td>
<td>Sarcomatoid</td>
<td>Splice site mutation</td>
<td>NR</td>
<td>NR**</td>
<td>PR (&gt;2 months) to crizotinib</td>
<td>Liu et al., J Clin Oncol 2015 (18)</td>
</tr>
<tr>
<td>11</td>
<td>61/M</td>
<td>NS</td>
<td>Sarcomatoid</td>
<td>Splice donor site mutation/H1094Y</td>
<td>NR</td>
<td>NR</td>
<td>PR (&gt;5 months) to crizotinib</td>
<td>Lee et al., J Thorac Oncol 2015 (22)</td>
</tr>
</tbody>
</table>

NSCLC, non-small cell lung cancer; METex14, MET exon 14 deletion; IHC, immunohistochemistry; M, male; F, Female; ES, ever-smoker; NS, never-smoker; Adeno, adenocarcinoma; SqCC, squamous cell carcinoma; NR, not reported; CR, complete response; PR, partial response; SD, stable disease; PD, progressive disease. *, MET/CEP7 =2.3 (low amplification); **, polysomy (9 copies) of the MET exon 14 mutation allele.
incidence of METex14 in gastrointestinal (GI) malignances indicating the clinical benefit if MET TKIs can potentially be expanded to GI malignancies. Thus Paik and colleagues’ Cancer Discovery paper and reports by others has suddenly provided the blueprint and started a race to finally get MET TKIs approved for clinical use after many years of searching for a frequent enough and actionable target. It is anticipated by the end of 2016, the significance of METex14 in NSCLC will be widely appreciated.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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