Dual MET and ERBB inhibition overcomes intratumor plasticity in osimertinib-resistant-advanced non-small-cell lung cancer (NSCLC)

A. Martinez-Marti1,2,3, E. Felip1,2,3*, J. Matito4, E. Mereu5,6, A. Navarro1,2, S. Cedrés1,2, N. Pardo1,2,3, A. Martinez de Castro1,2, J. Remon1,2, J. M. Miquel2, A. Guillaumet-Adkins5,6, E. Nadal7,8, G. Rodriguez-Esteban5,6, O. Arqués9, R. Fasani10, P. Nuciforo10, H. Heyn5,6, A. Villanueva7,11, H. G. Palmer9 & A. Vivancos4*

1Department of Medical Oncology, Vall d’Hebron University Hospital, Barcelona; 2Department of Medical Oncology, Vall d’Hebron Institute of Oncology (VHIO), Barcelona; 3Autonomous University of Barcelona (UAB), Barcelona; 4Cancer Genomics Group, Vall d’Hebron Institute of Oncology (VHIO), Barcelona; 5Single Cell Genomics Group, Centro Nacional de Análisis Genómico (CNAG) – Center for Genomic Regulation (CRG), Barcelona Institute of Science and Technology (BIST), Barcelona; 6Pompeu Fabra University (UPF), Barcelona; 7Chemoresistance and Predictive Factors Group, Program Against Cancer Therapeutic Resistance (ProCURE), Catalan Institute of Oncology (ICO) Bellvitge Biomedical Research Institute (IDIBELL), L’Hospitalet, Barcelona; 8Department of Medical Oncology, ICO, IDIBELL, L’Hospitalet, Barcelona; 9Stem Cells and Cancer Group; 10Molecular Oncology Group, Vall d’Hebron Institute of Oncology (VHIO), Barcelona; 11Xenopat S.L., Business Bioincubator, Bellvitge Health Science Campus, Barcelona, Spain

*Correspondence to: Dr Enriqueta Felip, Department of Medical Oncology, Vall d’Hebron Institute of Oncology, P. Vall d’Hebron 119-129, 08035 Barcelona, Spain. Tel: +34 93 274 6065; Fax: +34 93 274 6659; E-mail: efelip@vhio.net
Dr Ana Vivancos, Cancer Genomics Group, Vall d’Hebron Institute of Oncology, P. Vall d’Hebron 119-129, 08035 Barcelona, Spain. Tel: +34 93 254 34 50; E-mail: avivancos@vhio.net

Background: Third-generation epidermal growth factor receptor tyrosine kinase inhibitors (EGFR-TKIs) such as osimertinib are the last line of targeted treatment of metastatic non-small-cell lung cancer (NSCLC) EGFR-mutant harboring T790M. Different mechanisms of acquired resistance to third-generation EGFR-TKIs have been proposed. It is therefore crucial to identify new and effective strategies to overcome successive acquired mechanisms of resistance.

Methods: For Amplicon-seq analysis, samples from the index patient (primary and metastasis lesions at different timepoints) as well as the patient-derived orthotopic xenograft tumors corresponding to the different treatment arms were used. All samples were formalin-fixed paraffin-embedded, selected and evaluated by a pathologist. For droplet digital PCR, 20 patients diagnosed with NSCLC at baseline or progression to different lines of TKI therapies were selected. Formalin-fixed paraffin-embedded blocks corresponding to either primary tumor or metastasis specimens were used for analysis. For single-cell analysis, orthotopically grown metastases were dissected from the brain of an athymic nu/nu mouse and cryopreserved at –80°C.

Results: In a brain metastasis lesion from a NSCLC patient presenting an EGFR T790M mutation, we detected MET gene amplification after prolonged treatment with osimertinib. Importantly, the combination of capmatinib (c-MET inhibitor) and afatinib (ErbB-1/2/4 inhibitor) completely suppressed tumor growth in mice orthotopically injected with cells derived from this brain metastasis. In those mice treated with capmatinib or afatinib as monotherapy, we observed the emergence of KRAS G12C clones. Single-cell gene expression analyses also revealed intratumor heterogeneity, indicating the presence of a KRAS-driven subclone. We also detected low-frequent KRAS G12C alleles in patients treated with various EGFR-TKIs.

Conclusion: Acquired resistance to subsequent EGFR-TKI treatment lines in EGFR-mutant lung cancer patients may induce genetic plasticity. We assess the biological insights of tumor heterogeneity in an osimertinib-resistant tumor with acquired MET-amplification and propose new treatment strategies in this situation.

Key words: NSCLC, EGFR, T790M, MET, acquired resistance, intratumor plasticity
The analysis of cfDNA detected an additional EGFR T790M mutation (Figure 1C and D). Therapy initially reduced brain metastasis and treatment with osimertinib was sustained 21 months until the progressive metastatic brain lesion enlarged and required surgical resection (Figure 1C and E). Following brain surgery, osimertinib was continued for an additional 3 months due to clinical benefit. NGS analyses on this surgical specimen once again showed the deletion of exon 19 in EGFR and the TP53 Q317fs mutation and loss of EGFR T790M mutation (Figure 1D). Additionally, we identified a high-level amplification of the MET oncogene that was confirmed by fluorescent in situ hybridization [17] (FISH) (copy number of >40; MET/CEN7 ratio of >5) (Figure 1D and F), and high levels of c-MET protein by immunohistochemistry (Figure 1G). HER2 amplification was excluded as a resistance mechanism since no amplification was detected by FISH (ERBB2 gene copy number of 6; ERBB2/CEN17 [18] ratio of 1.1), or by immunohistochemistry (Figure 1F and data not shown). The emergence of this MET amplification in the context of an exon 19 deletion of EGFR and a regression of EGFR T790M mutation led us to combine EGFR and c-MET inhibitors to block the growth of the progressive brain metastasis [19]. Unfortunately, the patient suffered a rapid relapse and died soon after brain surgery.

At the time of surgery of brain metastasis, we obtained surgical tumor tissue to implant orthotopically in immunodeficient nude mice, generating an orthoxygenograft or PDOX model (Figure 2A). PDOXs present high concordance with the original clinical tumors [22, 23]. In this particular case, PDOX not only faithfully recapitulated the patient’s histology but also preserved MET amplification (Figure 2B and C) and similar EGFR status (total proteins by IHC and CNV using FISH) (supplementary Figure S3 and Table S4, available at Annals of Oncology online). This model allowed us to explore the efficacy of an EGFR inhibitor and c-MET inhibitor combined.

Passable biopsies were orthotopically implanted into the brain of 35 nude mice that were randomized and treated with vehicle, cisplatin/pemetrexed (standard chemotherapy), osimertinib (EGFR sensitizing and T790M resistance mutation inhibitor), afatinib (ErbB-1/2/4 inhibitor), capmatinib (c-MET inhibitor) and a combination of capmatinib and afatinib (Figure 2A). All treatments were administered during 21 days. Capmatinib alone or combined with afatinib showed superior efficacy, significantly increasing the overall survival of mice (Figure 2D). Strikingly, none of the capmatinib/afatinib treated mice displayed weight loss, increased intracranial pressure, presented any tumor evidence, or scaring in the brain or any other analyzed tissues after 300 days upon tumor implantation. These data demonstrate that capmatinib/afatinib treatment cured all mice. In the case of capmatinib monotherapy, two mice died 2 months after tumor implantation presenting brain tumors upon necropsy. Another two mice died after 9 months with no brain tumor, but one presented a lung metastasis and the other a mesenteric lesion. When treated with afatinib alone, all mice progressed with growing brain tumors and had to be killed earlier after treatment initiation. Similarly, PDOX treated with osimertinib did not show any benefit, confirming the resistance observed in the patient. In summary, c-MET, as opposed to EGFR blockade, was effective. The combination of the two, however, was the most potent therapy showing curative potential.

We then genotyped PDOX samples obtained from mice that progressed to the different treatments (Figure 2G). All xenograft
tissues showed the same exon 19 deletion in \textit{EGFR}, TP53 Q317fs mutation as well as \textit{MET} amplification detected in the original patient’s brain metastasis (Figure 2C, E and F). In addition, we observed a subclonal TP53 Q165K mutation in some xenografts. Interestingly, we detected the emergence of a subclonal \textit{KRAS} G12C mutation exclusively in xenograft tumors from mice treated with afatinib or capmatinib as monotherapy. This data suggested the surfacing of minor preexisting \textit{KRAS} G12C mutant clones as a mechanism of resistance to effective \textit{EGFR} or c-MET signaling blockade. In the original patient’s metastatic brain tumor biopsy, we actually confirmed the existence of \textit{EGFR} \textit{T790M} and \textit{KRAS} \textit{G12C} mutations at low-allele frequencies using ddPCR [24].

To study this phenomenon further, we evaluated clonal distribution within xenograft tumor samples by single-cell transcriptome analysis (massive parallel single-cell RNA-sequencing, MARS-Seq) [25, 26]. We sequenced 197 randomly selected cells from a tumor xenograft that grew in a brain of a capmatinib treated mouse and presented a \textit{KRAS} G12C mutation and an exon 19 deletion in \textit{EGFR} (Figure 2D and E). Using hierarchical clustering, or dimensional reduction representations (tSNE), we grouped single cells based on their differential transcriptional profiles and identified two main subpopulations (Figure 3A and B). We hypothesized that these two subpopulations may represent tumor subclones driven by either \textit{KRAS} or \textit{EGFR} activating mutations. To test this hypothesis, we first defined \textit{EGFR} and \textit{KRAS} [27] (supplementary Tables S2 and S3, available at 
\textit{Annals of Oncology} online). Remarkably, \textit{KRAS}-distinctive transcriptional signatures by comparing primary lung adenocarcinoma specimens’ mutant for \textit{EGFR} or \textit{KRAS} [27] (supplementary Tables S2 and S3, available at 
\textit{Annals of Oncology} online). Remarkably, \textit{KRAS}-activated genes were upregulated in the less abundant subclone, while \textit{EGFR}-related genes were activated in the remaining tumor cells (Figure 3C and D). Indeed, we observed a significantly increased expression of the \textit{KRAS}- or \textit{EGFR}-signature genes in the minor and major subpopulation, respectively, supporting their distinct activities in the putative tumor subclones (Student’s t-test, Figure 3E and F). The putative \textit{EGFR}-driven subclones showed a significant association to genes whose expression was altered following targeted \textit{EGFR} inhibition \textit{in vitro} (supplementary Figure S1A–D, available

Figure 1. Evolution and plasticity of acquired resistance mechanisms to osimertinib in NSCLC harboring \textit{EGFR} mutation. (A) Study of the molecular profiling of metastatic brain biopsy specimen of female patient with NSCLC exon 19 deletion and \textit{T790M} mutation treated with osimertinib. (A, C and D) ADC, adenocarcinoma. (B) Morphological appearance of primary and metastatic lung lesions (haematoxylin and eosin, 20x). (C) Serial of target tumor lesions measures and the lower panel displays anti-\textit{EGFR} treatment, imaging evaluation and genotyping along the evolution of the metastatic disease. (D) Molecular profiling of paired biopsies: baseline and at the time of progression to erlotinib and osimertinib. n. d., non-determined. (E) Representative brain MRI and CT scans at the time points indicated are provided; the largest brain target lesion is indicated with an arrow. (F) FISH analyses showing the presence of \textit{MET} amplification in the brain metastasis after relapse osimertinib (\textit{MET} gene, green signals; CEN7, red signals; 100 \(\times \)). (G) High expression of c\textit{MET} and \textit{EGFR} proteins was observed in brain lesion by immunohistochemistry. No expression for \textit{HER2} was found (2.5x).
at *Annals of Oncology* online), further supporting a clonal separation of the oncogenes. Collectively, these results support the existence of two distinct tumor subclones driven by either *KRAS* or *EGFR* activating mutations. Surprisingly, we further noticed the increased expression of immune system related genes in the *KRAS*-driven subclone (supplementary Figure S1E and F, available at *Annals of Oncology* online). We analyzed the PD-L1 expression by IHC in patient brain metastasis, PDOX *KRAS* WT and PDOX *KRAS* Mut (supplementary Figure S2, available at *Annals of Oncology* online).

The presence of minor *KRAS* mutant clones could be a clinically relevant mechanism of resistance to EGFR-TKIs and/or c-MET inhibitors and remain undetectable by standard techniques (NGS, qPCR, Sanger sequencing). Consequently, we used the most sensitive genetic assay, ddPCR [23] for a retrospectively genetic profiling of *EGFR*-mutated lung cancer patient samples (Table 1). In the biopsies at the time of progression to EGFR-TKIs from 13 *EGFR*-mutated patients, we detected five *EGFR* T790M and three *KRAS* G12C mutant tumors. These patients were originally considered wild type for these alterations when evaluated with NGS (Table 1). Furthermore, none of the seven tumor samples evaluated from surgical early-stage NSCLC patients with the presence of mutation in *EGFR* and naive to EGFR-TKIs presented *KRAS* G12C mutations. In one of the samples, we detected *EGFR* T790M, while *MET* amplification was detected after subsequent osimertinib. In the same line, previous studies showed how *MET* copy number gain causes gefitinib resistance in CNS lesions utilizing mouse in vivo imaging models [28]. At this point, we also detected *KRAS* G12C and *EGFR* T790M by ddPCR. Importantly, in a PDOX model, we demonstrated that this *MET* amplification is essential for lung cancer cell survival since capmatinib therapy proved very effective. Intriguingly, for the very first time, we show c-MET signaling inhibition with capmatinib to be more potent when combined with afatinib than as a single agent in our mouse model. This afatinib effect contrasted with its complete lack of activity as monotherapy. This benefit of combining afatinib could have been mediated by its previously described capacity to block ERBB3 or ERBB4 activations by heregulin ligand in *EGFR* mutant lung tumors [29]. This inhibition of ERBB3/4 or the inhibition of *EGFR* itself, are both possible mechanism that require further investigation. Our data suggest that this oncogenic ERBB activation would only be relevant for the survival of cancer cells addicted to hyperactive c-MET signaling. In this sense, c-MET and *EGFR* (ERBB1) form membrane heterodimers in normal and cancer cells leading to their trans-phosphorylation and activation of downstream MAPK pathway. Additionally, c-MET/KRAS/ERK signaling induces the transcription of EGF ligand and EGFR activation as a positive feedback loop. Further analyses will be required to confirm the relevance of such crosstalk between *EGFR* or ERBB3/4 with c-MET as a molecular determinant of response to combined c-MET and *EGFR* blockade in advanced lung cancer.

Our results also evidence the extreme plasticity of lung adenocarcinoma genomes that evolve to adapt to as well as survive the pharmacological pressure of third-generation EGFR-TKIs. Could

**Discussion**

In summary, we observed how a lung adenocarcinoma presenting an activating deletion of exon 19 in the *EGFR* gene acquired a second T790M mutation in the same gene upon treatment with erlotinib, while *MET* amplification was detected after subsequent osimertinib. In the same line, previous studies showed how *MET* copy number gain causes gefitinib resistance in CNS lesions utilizing mouse in vivo imaging models [28]. At this point, we also detected *KRAS* G12C and *EGFR* T790M by ddPCR. Importantly, in a PDOX model, we demonstrated that this *MET* amplification is essential for lung cancer cell survival since capmatinib therapy proved very effective. Intriguingly, for the very first time, we show c-MET signaling inhibition with capmatinib to be more potent when combined with afatinib than as a single agent in our mouse model. This afatinib effect contrasted with its complete lack of activity as monotherapy. This benefit of combining afatinib could have been mediated by its previously described capacity to block ERBB3 or ERBB4 activations by heregulin ligand in *EGFR* mutant lung tumors [29]. This inhibition of ERBB3/4 or the inhibition of *EGFR* itself, are both possible mechanism that require further investigation. Our data suggest that this oncogenic ERBB activation would only be relevant for the survival of cancer cells addicted to hyperactive c-MET signaling. In this sense, c-MET and *EGFR* (ERBB1) form membrane heterodimers in normal and cancer cells leading to their trans-phosphorylation and activation of downstream MAPK pathway. Additionally, c-MET/KRAS/ERK signaling induces the transcription of EGF ligand and EGFR activation as a positive feedback loop. Further analyses will be required to confirm the relevance of such crosstalk between *EGFR* or ERBB3/4 with c-MET as a molecular determinant of response to combined c-MET and *EGFR* blockade in advanced lung cancer.

Our results also evidence the extreme plasticity of lung adenocarcinoma genomes that evolve to adapt to as well as survive the pharmacological pressure of third-generation EGFR-TKIs. Could

**Figure 2.** Orthotopic patient-derived xenograft (PDOX) models using the same fresh metastatic brain biopsy of our patient at the time of progression to osimertinib. (A) Different PDOX cohorts that received treatment with vehicle, osimertinib, cisplatin/pemetrexed, afatinib, capmatinib and a combination of capmatinib and afatinib (capmatinib/afatinib). (A, B and E) Cis, cisplatin; Pem, pemetrexed; Cap, capmatinib; Afa, afatinib. (B) Representative images showing high similarity between patient brain metastasis and its PDX (20x). (C) Different PDOX cohorts that received treatment with vehicle, osimertinib, cisplatin/pemetrexed, afatinib, capmatinib and a combination of capmatinib and afatinib (capmatinib/afatinib). (A, B and E) Cis, cisplatin; Pem, pemetrexed; Cap, capmatinib; Afa, afatinib. (B) Representative images showing high similarity between patient brain metastasis and its PDX (20x). (C) MET gene amplification by FISH in the PDOX (MET gene, green signals, CEN7, red signals; 100x). (D) Kaplan–Meier survival analysis for the different PDOX treated cohorts. (E) Genotyping of PDOX samples obtained from mice that progressed to the different treatments. VAF, variant allele frequency. (F) Representation of clonal evolution of the acquired resistance.
this be a consequence of selecting de novo mutations in lung cancer genomes or is it reflective of the early coexistence of multiple genetic clones with distinctive capacities to resist target-directed therapies? Our findings support the hypothesis of lung adenocarcinomas consisting of a complex map of genetic clones ready for selection under effective pharmacological pressure. We clearly observed the emergence of KRAS G12C mutant clones upon blocking two upstream activating components of the MAPK pathway such as EGFR or c-MET. Similarly, oncogenic KRAS mutations were described as resistance mechanisms to anti-EGFR antibodies in colorectal cancer [30, 31], a phenomenon that can also involve clonal enrichment upon treatment.

Indeed, we observed that drugs blocking EGFR or c-MET signaling preferentially promoted the emergence of genetic alterations in EGFR, MET and KRAS genes; all essential components of the oncogenic TKR/KRAS/MAPK pathway. This particular genetic evolution confirms the strict addiction of lung tumors to TKR/KRAS/MAPK pathway as a driving force of drug-resistance and disease progression. Consistent with our aforementioned observations, subsequent therapy should be assessed as a combination of the EGFR inhibitor with c-MET inhibitors.

In these highly heterogeneous lung tumor samples, we also noted a subpopulation of cells presenting a distinctive KRAS gene expression signature enriched in immune-related components. Indeed, initial clinical data indicate that KRAS mutant lung adenocarcinomas could be more sensitive to immune checkpoint inhibitors. Thus, we also suggest immunotherapy as a later line of treatment of those patients with EGFR mutant lung tumors that progress to consecutive lines of EGFR-TKIs and present emergence of KRAS mutant as well as potentially immunosensitive clones.

**Figure 3.** Single-cell transcriptome profiles point to the presence of a KRAS-driven subclone. (A) Hierarchical clustering of 197 single cells (columns) derived from a capmatinib-resistant PDOX using the most variable gene sets [32]. Cells are grouped into two putative subclones (column labels) and correlating gene sets are summarized in aspects. Displayed are the most variable aspects (rows) and their importance (row colors). (B) Gene expression variances between cells displayed as t-distributed stochastic neighbor embedding (t-SNE) representation using previous defined distances and cluster identities (as in A). (C) Gene expression signatures derived from KRAS (upper panel) or EGFR (lower panel) mutant primary lung adenocarcinomas [27]. Gene expression levels of single cells are displayed as relative intensities [22]. Displayed are the 25 most variant genes and signatures are summarized in the panel above (orange: overrepresented; green: underrepresented). (D) Mutational signature intensities of single cells. Cells are separated by their signature expression levels for EGFR and KRAS mutations. Cells were assigned to clusters as in (A). Direct comparison of KRAS (E) or EGFR (F) signature scores between the putative subclones (KRAS: red; EGFR: black). Significant differences between groups (Student’s t-test) are indicated.
Finally, our data indicated that lung adenocarcinomas might evolve rapidly due to the surfacing of minor pre-existing genetic clones resistant to specific targeted therapies. Therefore, more complex therapies combining EGFR-TKIs with MET inhibitors and/or immunotherapy could be considered for lung cancer patients at earlier stages. This novel approach could prevent drug resistance and disease progression later on. For this reason, the clinical implementation of genetic technologies with higher sensitivity will be crucial in defining the genetic landscape of polyclonal tumors in patients’ candidate to target-directed therapies.

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Disclosure

All authors have declared no conflicts of interest.

References


Table 1. Twenty EGFR-mutated lung cancer samples were assessed retrospectively by a ddPCR assay

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<th>Previous lines of treatment</th>
<th>Previous lines of TKI</th>
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<th>Baseline EGFR T790M (ddPCR)</th>
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Thirteen tumor samples from EGFR-mutated patients at the time of progression to EGFR-TKIs were analyzed. Seven biopsies were evaluated from surgical early-stage NSCLC patients with the presence of EGFR mutation and naive for EGFR-TKI therapy.


