

The allelic context of the C797S mutation acquired upon treatment with third generation EGFR inhibitors impacts sensitivity to subsequent treatment strategies

Matthew J. Niederst<sup>1,2</sup>, Haichuan Hu<sup>1,2</sup>, Hillary E. Mulvey<sup>1,2</sup>, Elizabeth L. Lockerman<sup>1,2</sup>, Angel R. Garcia<sup>1,2</sup>, Zofia Piotrowska<sup>1,2</sup>, Lecia V. Sequist<sup>1,2</sup> and Jeffrey A. Engelman<sup>1,2</sup>

<sup>1</sup>Massachusetts General Hospital Cancer Center, Massachusetts General Hospital, 55 Fruit St Boston, MA 02114, USA

<sup>2</sup>Department of Medicine, Harvard Medical School, 25 Shattuck St Boston, MA 02115, USA

### Running Title

C797S promotes resistance to third generation EGFR inhibitors

### Keywords

EGFR, NSCLC, C797S, TKI, Resistance

### Financial Support

This study was funded by support from the NIH R01CA137008 (J.A.E.), the Department of Defense (L.V.S. and J.A.E.), LunGevity (L.V.S. and J.A.E.), Uniting Against Lung Cancer (Z.P. and M.J.N.), Lung Cancer Research Foundation (M.J.N), Targeting a Cure for Lung Cancer, and Be a Piece of the Solution.

### Corresponding Author

Jeffrey A. Engelman, 149 13<sup>th</sup> st 7<sup>th</sup> Floor, Charlestown, MA 02129. Phone: (617)-724-7298, Fax: 617-724-9648, Email: jengelman@mgh.harvard.edu

### Conflicts of Interest

J.A.E. is a consultant for Novartis, Sanofi, Genentech, Clovis and Astra Zeneca; owns equity in Gatekeeper Pharmaceuticals, which has interest in T790M inhibitors; has research agreements with Novartis and Astra Zeneca. Z.P. has provided consulting services for Clovis Oncology. L.V.S. has provided uncompensated consulting services to Clovis Oncology, AstraZeneca, Novartis, Boehringer-Ingelheim, Merrimack Pharmaceuticals, Genentech and Taiho Pharmaceuticals.

**Word Count** 4437

**Figures** 5 main, 1 supplemental

## Statement of translational relevance

Acquired resistance to first generation EGFR inhibitors is mediated by a secondary mutation to *EGFR*, T790M, in just over half of *EGFR* mutant NSCLC patients. Third generation EGFR inhibitors that inhibit EGFR with T790M have recently entered clinical testing and have led to remissions in a majority of these cancers. Despite these promising initial results, acquired resistance to these drugs will likely develop. Little is known, however, about mechanisms of resistance to third generation EGFR TKIs. Herein, we identify the C797S *EGFR* mutation in cells made resistant to a third generation inhibitor and demonstrate that it is sufficient to promote resistance to third generation TKIs. Moreover, whether the C797S mutation occurs in cis or trans with T790M determines which subsequent EGFR TKIs, alone and in combination, may be effective. These data suggest an important clinical value in sequencing for this mutation in patients with acquired resistance to third generation TKI.

## Abstract

**Purpose:** A secondary *epidermal growth factor receptor* (*EGFR*) mutation, T790M, is the most common resistance mechanism in *EGFR* mutant adenocarcinomas that have progressed on erlotinib. Third generation *EGFR* inhibitors capable of inhibiting mutant *EGFR* with T790M produce responses in nearly two thirds of patients. However, acquired resistance mechanisms in patients treated with these drugs are yet to be described.

**Experimental Design:** To study acquired resistance to third generation *EGFR* inhibitors, T790M-positive cells derived from an erlotinib-resistant cancer were made resistant to a third generation TKI and then characterized using cell and molecular analyses.

**Results:** Cells resistant to a third generation TKI acquired an additional *EGFR* mutation, C797S, which prevented suppression of *EGFR*. Our results demonstrate that the allelic context in which C797S was acquired may predict responsiveness to alternative treatments. If the C797S and T790M mutations are in trans, cells will be resistant to third generation *EGFR* TKIs, but will be sensitive to a combination of first and third generation TKIs. If the mutations are in cis, no *EGFR* TKIs alone or in combination can suppress activity. If C797S develops in cells wild type for T790 (when third generation TKIs are administered in the first line setting), the cells are resistant to third generation TKIs, but retain sensitivity to first generation TKIs.

**Conclusions:** Mutation of C797S in *EGFR* is a novel mechanism of acquired resistance to third generation TKIs. The context in which the C797S develops with respect to the other *EGFR* alleles impacts the efficacy of subsequent treatments.

## Introduction

The epidermal growth factor receptor (EGFR) tyrosine kinase inhibitors (TKIs) gefitinib, erlotinib, and afatinib are effective treatments for *EGFR* mutant non-small cell lung cancers (NSCLCs) (1-5). Although most patients with *EGFR* mutant NSCLC respond to these therapies, the responses are not permanent, and patients typically develop resistance after an average of one year on treatment (6). There are several mechanisms of acquired resistance to erlotinib, including the development of a “gatekeeper” point mutation, T790M, which prevents the TKI from effectively inhibiting EGFR (7, 8), reactivation of downstream signaling pathways via bypass tracks (9-14), and phenotypic/histological changes such as Epithelial to Mesenchymal Transition (EMT) or Small Cell Lung Cancer (SCLC) transformation (12, 14, 15). T790M is the most common resistance mechanism in these cancers and is observed in over 50% of resistant biopsies (12, 14).

Second generation EGFR inhibitors, including afatinib (BIBW2992) and dacomitinib (PF00299804), are irreversible EGFR inhibitors that bind to Cys797 and have been shown in preclinical experiments to effectively inhibit EGFR with activating mutations (Exon 19 deletion or L858R) as well as those with the T790M resistance mutation (16, 17). However, their activity in patients with erlotinib-resistant cancers harboring T790M has been minimal (18, 19). The discordance between laboratory and clinical results is likely due to a poor therapeutic window. These drugs are equally potent against wild type EGFR and EGFR T790M, and thus the toxicity resulting from inhibiting wild type EGFR (rash and diarrhea) precludes the use of doses that would be needed to effectively suppress T790M (20). More recently, third generation EGFR TKIs including WZ4002, CO-1686, AZD9291 and EGF816 have been developed to target mutant EGFR harboring T790M (21-24). This class of inhibitor also binds covalently to Cys797, and largely spares WT EGFR, thereby decreasing toxicity and permitting the use of doses that fully suppress T790M. This large therapeutic window likely underlies the greater than 50% response rates observed in clinical trials with CO-1686 and AZD-9291 in erlotinib-resistant, T790M-positive NSCLCs (25, 26). Based on these promising results, both drugs have received FDA, “breakthrough therapy designation” and this class of inhibitors is on the verge of becoming widely implemented for treatment of this patient population. Previous studies have generated acquired resistance to third generation inhibitors in well-studied cell lines, and have identified mechanisms that have also been observed in cancers with acquired resistance to first generation EGFR inhibitors. These include EMT (22), sustained activation of the MAPK kinase pathway (27), and IGF1R bypass signaling as resistance mechanisms (28). Herein, we utilize

T790M positive cells derived from a biopsy of an erlotinib-resistant tumor to cultivate resistance to a third generation EGFR TKI. In doing so, we identify a widely anticipated resistance mechanism specific to third generation EGFR inhibitors, a C797S resistance mutation, that prevents this class of drugs from effectively suppressing EGFR activity. We also determine that the presence of T790M, whether in cis or trans to C797S, markedly impacts efficacy of subsequent therapeutic strategies.

## **Materials and methods**

### Reagents and cell culture

MGH121, MGH121 Res # 1 and PC9 cells were cultured in RPMI with 10% serum. 293FT cells were cultured in DMEM with 10% serum. PC9 cells were a gift from Pasi Janne, 293FT cells are from Invitrogen. MGH121 cells were generated from a pleural effusion of an erlotinib-resistant NSCLC patient on July 19, 2011 and were originally developed in ACL4 supplemented with 10% serum. Once completed the cell line was sequenced to confirm that it matched the patient effusion sample. Experiments involving the 293FT cells were completed within 6 months of purchasing from Invitrogen and did not undergo any further testing. PC9 cells were verified by STR analysis within 6 months to 1 year of experimentation. Gefitinib, Afatinib, WZ4002, CO-1686 and AZD-9291 were purchased from Selleck and re-suspended in DMSO. pEGFR antibody (pY1068) was from Abcam, total EGFR was from Santa Cruz Biotechnology. pERK (T202/Y204), total ERK, pS6 (S240/244), total S6, Actin, pAKT (T308) and total AKT were purchased from Cell Signaling Technologies. All antibodies were used at a concentration of 1:1000.

### Generating *in vitro* resistant cell line

MGH121 was derived from a pleural effusion of an erlotinib-resistant patient. The procedure for establishing this line has been described previously (15, 30, 41). To generate resistance in this model, MGH121 parental cells were grown in increasing doses of WZ4002 starting at 10nM and increasing to 30, 100, 300, and 1000nM incrementally once the cells began to grow through the given dose.

### Generating lentiviral constructs, lentivirus and stable expression cell lines

Lentiviral constructs and lentivirus were generated using the ViraPower Lentiviral Directional TOPO Expression Kit (Life Technologies) per the manufacturer's protocol. Briefly,

*EGFR* Exon 19 del and Exon 19 del/T790M plasmids were purchased from Addgene (32062, 32072). Quikchange site-directed mutagenesis kit (Stratagene) was used to introduce the C797S mutation into both constructs using the following primers: C797S F – CATGCCCTTCGGCTCCCTCCTGGACTA and C797S R – TAGTCCAGGAGGGAGCCGAAGGGCATG. The resulting *EGFR* Exon 19del/C797S and *EGFR* Exon 19 del/C797S/T790M constructs were used as a template to amplify *EGFR* for ligation into the pLENTI6/V5-D-TOPO vector. Virus was made by transfecting the pLENTI6 constructs along with helper plasmids in 293FT cells. Virus production, collection and infection were completed following the manufacturer's protocol. The PC9 and MGH121 infected cells were selected beginning 24 hours post-infection using Blasticidin at a concentration of 5µg/ml.

#### Overexpressing EGFR mutants in 293FT cells

*EGFR* mutant constructs (see section on generating lentivirus) were transfected into 200k/well 293FT cells in a 6-well dish using TransIT-LT1 transfection reagent (Mirus) per the manufacturer's protocol. 48 hours post-infection, cells were treated with TKI inhibitor for 6 hours prior to lysis.

#### Cell viability assays

Three day viability assays were carried out by plating 4000 cells/well into black-bottom 96-well plates. The following day, cells were drugged with TKI across a 10 dose range from 1nM to 30µM. 72 hours post drug treatment, cell viability was measured using Cell-Titer Glo (Promega).

Crystal violet viability assays were completed by plating 100k cells/well into 6-well plates. The following day, cells were drugged with TKI across a 5 dose range from 10nM to 1000nM and re-drugged after 4 days. The crystal violet staining was carried out 7 days following the initial drug treatment.

#### DNA sequencing and allele quantification assay

gDNA was prepared from the MGH121 parental and MGH121 Res # 1 cells using the DNeasy kit from Qiagen. *EGFR* Exons 19 and 20 were PCR amplified using the following primers (42): Exon 19 F – GGTAACATCCACCCAGATCAC, Exon 19 R – TGAGCAGGGTCTAGAGCAGAG, Exon 20 F – GAAGCCACACTGACGTGC and Exon 20 R – CTCCTTATCTCCCCTCCCCG. Following amplification, Sanger sequencing was completed by

the Sequencing group of the CCIB DNA Core Facility at Massachusetts General Hospital. To quantify the allele frequencies, the PCR products were ligated into the TOPO TA for sequencing vector (Life Technologies). The ligations were transformed into competent bacteria and plated. Each bacterial colony should carry a plasmid that contains DNA that started as a single PCR product. For each sequencing reaction, plasmid DNA from ~100 bacterial colonies was isolated and sequenced (CCIB DNA Core Facility at Massachusetts General Hospital). Sequencing data were analyzed and the relative frequency of the Exon 19 del, T790M and C797S mutations were quantified.

### Quantification of EGFR gDNA levels

*EGFR* gDNA levels were quantified by a qPCR based method. 10 ng of MGH121 pt and MGH121 Res # 1 DNA were used as a template for a SBYR green based qPCR assay using primers 20F and 20R to amplify genomic DNA of *EGFR*. LINE-1 was used as a loading control: LINE1 F-AAAGCCGCTCAACTACATGG, LINE 1 R-TGCTTTGAATGCGTCCCAGAG. Normal female DNA served as a diploid control.

## **Results**

Cell lines derived from biopsies of cancers that have become resistant to targeted therapies have been a valuable tool for studying acquired resistance to targeted therapies (29, 30). In addition, cultivating resistance to targeted therapies *in vitro* has yielded clinically validated resistance mechanisms (10, 14, 31-34). To study acquired resistance to third generation *EGFR* TKIs, we took advantage of a cell line model that was derived from a biopsy of a resistant *EGFR* mutant (Exon 19 del) tumor that had developed T790M in the clinic after 7 months on erlotinib. This cell line, MGH121, was resistant to the first generation *EGFR* TKI gefitinib, consistent with the presence of the T790M resistance mutation, but was highly sensitive to the third generation TKI WZ4002 (Figure 1A). To model acquired resistance to third generation inhibitors in these cells, we cultured them in increasing doses of WZ4002, starting at 10nM and raising the concentration incrementally until the cells were growing in 1μM. This common approach for generating resistance *in vitro* has proven to consistently produce clinically relevant resistance mechanisms (10, 29). The resulting resistant model, MGH121 Res # 1, was highly resistant to WZ4002 (Figure 1A, B), and in addition, WZ4002 treatment failed to suppress *EGFR* phosphorylation and downstream signaling in these cells (Figure 1C). We hypothesized



that this failure of the third generation TKI to inhibit the target may result from an additional *EGFR* mutation. Sequencing of the kinase domain of EGFR revealed a single point mutation resulting in a cysteine to serine change at position 797 (C797S). This mutation was present in the MGH121 Res # 1 cells, but not the MGH121 parental cells (Figure 1D). C797 is located opposite T790 in the ATP binding pocket and forms a covalent bond with all third-generation TKIs and is necessary for the inhibitor to suppress EGFR (21). Thus, C797S is an excellent candidate for a resistance mutation.

The higher levels of EGFR protein in the MGH121 Res # 1 cells compared to the parental cells (Figure 1C) combined with an increased relative abundance of the mutated nucleotide that encodes for the serine on the chromatogram (Figure 1D) raised the possibility that amplification of *EGFR* carrying C797S may have occurred in the MGH121 Res # 1 cells. We carried out qPCR of the *EGFR* gene using genomic DNA as a template to measure the relative *EGFR* copy number. Compared to normal diploid control DNA, the parental MGH121 cells have over 3.5 fold more *EGFR* gDNA equal to roughly 7 copies of *EGFR* per cell on average (Supplemental Figure 1A). MGH121 Res # 1 have over 9 fold more *EGFR* gDNA compared to normal control DNA, equal to roughly 18 copies of EGFR and consistent with amplification versus the MGH121 parental cells. Further, variant allele frequency analysis revealed that the C797S mutant allele was specifically amplified in the MGH121 Res # 1, as the majority of EGFR alleles harbor this mutation (Supplemental Figure 1B).

As a group, the second and third generation irreversible EGFR inhibitors are able to suppress the *in vitro* growth of cells with an *EGFR* activating mutation and T790M. Indeed, MGH121 parental cells are also sensitive to the second generation inhibitor afatinib and other third generation inhibitors CO-1686 and AZD-9291 (Figure 2A left). These inhibitors similarly bind covalently to C797 of EGFR (22, 23, 35) and are ineffective at suppressing the growth of MGH121 Res # 1 cells (Figure 2A right) (although, as discussed in the Introduction, the dose of the second generation inhibitors required to inhibit T790M cannot be achieved in patients). The sensitivity of the MGH121 parental and Res # 1 cells to different EGFR TKIs correlate with the ability of the inhibitors to block EGFR signaling. In the MGH121 parental cells, gefitinib failed to suppress EGFR phosphorylation and downstream pathway components ERK and S6, whereas afatinib, WZ4002, CO-1686 and AZD-9291 were all able to do so (Figure 2B). In contrast, none of the EGFR TKIs suppressed EGFR signaling in MGH121 Res # 1 cells. To confirm that the sustained EGFR phosphorylation in the presence of the third generation TKI was due to the C797S mutation, we engineered different *EGFR* mutants and overexpressed them in 293T cells.



These include *EGFR* Exon 19 Del/T790M and *EGFR* Exon 19 Del/T790M/C797S (Figure 2C). In this system, EGFR Exon 19 del/T790M phosphorylation was effectively inhibited by second and third generation TKIs, while phosphorylation of EGFR Exon 19 Del/T790M/C797S was not suppressed by any of the inhibitors tested (Figure 2C). To determine if the C797S mutation alone was sufficient to promote resistance to second and third generation TKIs in an *EGFR* mutant cell line, we stably expressed the *EGFR* Exon 19 Del/T790M/C797S in MGH121 parental cells. Neither afatinib nor WZ4002 were able to block EGFR phosphorylation or the downstream signaling in these cells (Figure 2D). Accordingly, the growth of these cells was resistant to all generations of EGFR TKIs (Figure 2E). Together, these data demonstrate that the C797S mutation is sufficient to promote resistance to second and third generation EGFR inhibitors by preventing suppression of the target.

We next wanted to identify whether the C797S mutation occurred in cis (on the same allele) or trans (on a different allele) with T790M in MGH121 Res # 1 cells. To address this question, we amplified exon 20 by PCR (exon 20 contains the nucleotides encoding for both T790 and C797) using a genomic DNA template and assessed 119 individual PCR products via a TOPO cloning protocol (see methods). This analysis revealed that the T790M and C797S were in cis in MGH121 Res # 1 cells, as the C797S mutation coexisted with T790M on 85% of alleles (n = 101). The other 15% of alleles had no mutations in exon 20. Thus, there were no exon 20 alleles harboring only T790M or C797S (n = 18, Figure 3A).

Whether the C797S mutation is in cis or trans with T790M may have important biological implications. As demonstrated above, *EGFR* with an activating mutation, T790M and C797S all in cis, as observed in the MGH 121 Res #1 cells, leads to resistance to all three generations of EGFR TKI (Figure 2). To determine what would happen if the C797S and T790M mutations were both present in the same cell but on different *EGFR* alleles (i.e. in trans), we overexpressed several potential *EGFR* mutant allele configurations in 293T cells and examined their response to different EGFR TKIs. First, we tested the Exon 19 del/T790M and Exon 19 del/C797S double mutants independently. As expected for Exon 19 del/T790M, the first generation TKI gefitinib did not inhibit EGFR phosphorylation while afatinib and WZ4002 suppressed it (Figure 3B, lanes 1-4). Conversely, EGFR with the Exon 19 del/C797S double mutant was inhibited by gefitinib and afatinib, but not WZ4002 (Fig 3B, lanes 5-8). Thus, a C797S mutant, even in the absence of T790M, would clearly lead to resistance to a third generation TKI. This scenario might develop when *EGFR* mutant cancers are treated with third generation inhibitors in the first-line setting, and importantly, such cancers might be sensitive to

single-agent first generation EGFR inhibitors. In addition, these data predict that a combination of first and third generation inhibitors would be effective if the C797S and T790M mutations were in trans. When Exon 19 del/T790M and Exon 19 del/C797S were co-expressed in the same cells to model the trans scenario, treatment with either gefitinib or WZ4002 alone each partially suppressed EGFR phosphorylation, consistent with each drug suppressing a fraction of the EGFR protein expressed in the cells. The combination of gefitinib and WZ4002, however, completely inhibited EGFR phosphorylation (Figure 3B, lanes 9 -13). Finally, EGFR in the triple mutant (cis scenario) was resistant to all three generations of TKI as well as the combination of gefitinib and WZ4002 (Figure 3B, lanes 14-18). Of note, the second generation inhibitor, afatinib, suppressed EGFR when C797S and T790M were in trans. However, we know from clinical experience that afatinib is unable to inhibit T790M in the clinic due to a lack of a therapeutic window, and thus the combination of a first and third generation TKI holds more promise.

We also modeled both the cis and trans configurations in the parental MGH121 cells by stably expressing either the triple mutant to recapitulate the cis scenario or the Exon 19 del/C797S for the trans situation (MGH121 parental cells carry an endogenous Exon 19 del/T790M allele). We observed results consistent with those from the previous over-expression experiment: The trans setting induced resistance to third generation TKI, but the combination of gefitinib and WZ4002 inhibited EGFR signaling (Figure 3C) and cell growth (Figure 3D). However, this combination was not effective when all the mutations were in cis. These experiments demonstrate an important difference in drug response if the T790M and C797S mutations occur on the same or on different alleles, a result that has clinical implications.

To date, the majority of clinical trials of third generation EGFR TKIs have been conducted in the setting of erlotinib-resistant disease, but clinical trials testing these therapies in TKI naïve patients are currently ongoing (NCT02296125, NCT02186301). The finding that the C797S mutation in the absence of T790M is sufficient to cause resistance to third generation TKIs but retains sensitivity to gefitinib, raises the intriguing possibility that patients with acquired resistance to third generation TKI in the first line setting may subsequently respond to first or second generation TKIs in the second line setting. To test this hypothesis, we stably expressed *EGFR* with Exon 19 del/C797S in a TKI-naïve cell line, PC9, which is sensitive to all classes of EGFR inhibitors. PC9 Exon 19 Del/C797S cells were indeed resistant to WZ4002, but sensitive to gefitinib and afatinib (Figure 4 A, B). By comparison, PC9 triple mutant cells were resistant to all EGFR inhibitors that were tested. This result supports the notion that patients that are

treated with third generation TKI as their first EGFR inhibitor and acquire resistance driven by C797S may subsequently respond to first generation TKI. Of note, the concentration of afatinib required to suppress the growth of cells expressing the Exon 19 Del/C797S construct was markedly higher than the PC9 parental cells (Figure 4B), suggesting that the C797S mutation leads to reduced potency of this drug. It remains to be determined whether the dose of afatinib necessary to inhibit mutant EGFR with a C797S mutation alone is achievable in patients given the aforementioned narrow therapeutic window.

## Discussion

The efficacy of tyrosine kinase inhibitors has been limited by acquisition of resistance mutations that prevent inhibition of the target. For patients treated with the first generation EGFR TKIs gefitinib and erlotinib, the T790M resistance mutation has been observed in over half of resistant biopsies (12, 14). In this paradigm and others, next generation TKIs have been developed to suppress oncogenic kinases that harbor resistance mutations. For T790M-positive *EGFR* mutant NSCLCs, third generation EGFR TKIs have been particularly effective and are poised to be approved by the FDA in this setting. In this study, we cultivated resistance to a third generation EGFR TKI in a T790M-positive cell line established from an erlotinib-resistant biopsy. In these resistant cells, we report that another mutation to *EGFR*, C797S, prevents EGFR inhibition and promotes resistance to third generation EGFR TKIs. The initial study characterizing WZ4002 revealed that the covalent interaction between EGFR and the inhibitor is mediated by this cysteine residue and is necessary for the activity of third generation inhibitors in an *in vitro* kinase assay, and thus mutation of this amino acid is an excellent candidate for a resistance mutation (21). To our knowledge our data serve as the first evidence that C797S can develop in an *EGFR* mutant cancer model treated chronically with a third generation EGFR TKI.

Our results suggest that treatment history and genetic background may have important therapeutic implications for cancers that have acquired a C797S mutation (Figure 5). For example, patients treated with a third generation TKI as their first EGFR inhibitor may develop C797S in the absence of a T790M mutation. Our data indicate that first generation TKIs do not depend on a cysteine at position 797 in order to block EGFR. As a result, a cancer that developed C797S as a resistance mechanism to first-line therapy with a third generation EGFR TKI may subsequently respond to a first generation inhibitor. In agreement with our findings,

erlotinib has previously shown to be capable of suppressing EGFR with a mutation at C797 (36). This finding may also impact the current debate regarding whether it is better to give a third generation inhibitor in the first line or resistance setting. Importantly, these results suggest that combining first and third generation TKIs in the first line setting may be particularly powerful since neither a T790M nor a C797S mutation alone would be sufficient to drive resistance to this combination.

For T790M positive, erlotinib-resistant NSCLCs that develop a C797S mutation following treatment with a third generation TKI, the configuration of the T790M and C797S mutations affect how the cells could respond to therapy. Indeed, if the two mutations are in trans (on separate alleles) we have shown that a combination of first and third generation TKIs can restore EGFR inhibition. Conversely, if the two mutations are in cis (on the same allele), the cells are refractory to any of the EGFR TKIs we tested as well as the combination of first and third generation inhibitors. Clinical assessment of the cis versus trans configurations can likely be determined by next generation sequencing approaches, as the T790M and C797S mutations are in close enough proximity to co-exist on a significant number of individual sequencing reads. PKC inhibitors such as midostaurin (PKC412) have recently been shown to non-covalently inhibit EGFR with T790M and thus may be able to suppress mutant EGFR with T790M and C797S in cis (37). However, these drugs are limited by their lack of specificity and thus the potential for therapeutic window in this setting is uncertain.

The covalent interaction with C797 has also been demonstrated to be important to the activity of the pan-HER inhibitor CI-1033 (38, 39) and exogenous expression of a C797A mutant can confer resistance to another second generation inhibitor, HKI-272 (36). Our data reveal that at a concentration of 1 $\mu$ M, afatinib can inhibit mutant EGFR with C797S in the absence of T790M. Importantly, however, expression of mutant EGFR with C797S in PC9 cells results in a significant increase in the IC<sub>50</sub> of afatinib compared to parental PC9 cells. Of note, a similar reduction in activity of second generation inhibitors towards EGFR is caused by T790M (36, 40). This decreased activity of second generation TKIs toward mutant EGFR with T790M diminishes the therapeutic window in these cancers resulting in the lack of clinical efficacy. It is likely that the same will be true for resistant *EGFR* mutant cancers harboring C797S.

Third generation EGFR inhibitors are proving to be effective treatments for erlotinib-resistant cancers with T790M mutations and will soon become clinically available. Our results indicate that mutation of the C797 residue may be a mechanism by which these cancers

progress on this class of drugs. Sequencing biopsy samples from patients whose tumors have progressed on third generation TKIs and determining if the C797S mutation is in cis or trans with T790M should be a priority going forward. Designing a treatment strategy that can suppress triple mutant EGFR may soon be needed.

## References

1. Mok TS, Wu YL, Thongprasert S, Yang CH, Chu DT, Saijo N, et al. Gefitinib or carboplatin-paclitaxel in pulmonary adenocarcinoma. *N Engl J Med*. 2009;361:947-57.
2. Mitsudomi T, Morita S, Yatabe Y, Negoro S, Okamoto I, Tsurutani J, et al. Gefitinib versus cisplatin plus docetaxel in patients with non-small-cell lung cancer harbouring mutations of the epidermal growth factor receptor (WJTOG3405): an open label, randomised phase 3 trial. *Lancet Oncol*. 2010;11:121-8.
3. Maemondo M, Inoue A, Kobayashi K, Sugawara S, Oizumi S, Isobe H, et al. Gefitinib or chemotherapy for non-small-cell lung cancer with mutated EGFR. *N Engl J Med*. 2010;362:2380-8.
4. Rosell R, Carcereny E, Gervais R, Vergnenegre A, Massuti B, Felip E, et al. Erlotinib versus standard chemotherapy as first-line treatment for European patients with advanced EGFR mutation-positive non-small-cell lung cancer (EURTAC): a multicentre, open-label, randomised phase 3 trial. *Lancet Oncol*. 2012;13:239-46.
5. Sequist LV, Yang JC, Yamamoto N, O'Byrne K, Hirsh V, Mok T, et al. Phase III Study of Afatinib or Cisplatin Plus Pemetrexed in Patients With Metastatic Lung Adenocarcinoma With EGFR Mutations. *J Clin Oncol*. 2013;31:3327-34.
6. Ohashi K, Sequist LV, Arcila ME, Lovly CM, Chen X, Rudin CM, et al. Characteristics of lung cancers harboring NRAS mutations. *Clin Cancer Res*. 2013;19:2584-91.
7. Kobayashi S, Boggon TJ, Dayaram T, Janne PA, Kocher O, Meyerson M, et al. EGFR mutation and resistance of non-small-cell lung cancer to gefitinib. *N Engl J Med*. 2005;352:786-92.
8. Pao W, Miller VA, Politi KA, Riely GJ, Somwar R, Zakowski MF, et al. Acquired resistance of lung adenocarcinomas to gefitinib or erlotinib is associated with a second mutation in the EGFR kinase domain. *PLoS medicine*. 2005;2:e73.
9. Niederst MJ, Engelman JA. Bypass mechanisms of resistance to receptor tyrosine kinase inhibition in lung cancer. *Sci Signal*. 2013;6:re6.
10. Engelman JA, Zejnullahu K, Mitsudomi T, Song Y, Hyland C, Park JO, et al. MET amplification leads to gefitinib resistance in lung cancer by activating ERBB3 signaling. *Science*. 2007;316:1039-43.
11. Takezawa K, Pirazzoli V, Arcila ME, Nebhan CA, Song X, de Stanchina E, et al. HER2 amplification: a potential mechanism of acquired resistance to EGFR inhibition in EGFR-mutant lung cancers that lack the second-site EGFR T790M mutation. *Cancer Discov*. 2012;2:922-33.
12. Yu HA, Arcila ME, Rekhtman N, Sima CS, Zakowski MF, Pao W, et al. Analysis of tumor specimens at the time of acquired resistance to EGFR-TKI therapy in 155 patients with EGFR-mutant lung cancers. *Clin Cancer Res*. 2013;19:2240-7.
13. de Bruin EC, Cowell C, Warne PH, Jiang M, Saunders RE, Melnick MA, et al. Reduced NF1 expression confers resistance to EGFR inhibition in lung cancer. *Cancer Discov*. 2014;4:606-19.



14. Sequist LV, Waltman BA, Dias-Santagata D, Digumarthy S, Turke AB, Fidias P, et al. Genotypic and histological evolution of lung cancers acquiring resistance to EGFR inhibitors. *Sci Transl Med*. 2011;3:75ra26.
15. Niederst MJ, Sequist LV, Poirier JT, Mermel CH, Lockerman EL, Garcia AR, et al. RB loss in resistant EGFR mutant lung adenocarcinomas that transform to small-cell lung cancer. *Nature communications*. 2015;6:6377.
16. Li D, Ambrogio L, Shimamura T, Kubo S, Takahashi M, Chirieac LR, et al. BIBW2992, an irreversible EGFR/HER2 inhibitor highly effective in preclinical lung cancer models. *Oncogene*. 2008;27:4702-11.
17. Engelman JA, Zejnullahu K, Gale CM, Lifshits E, Gonzales AJ, Shimamura T, et al. PF00299804, an irreversible pan-ERBB inhibitor, is effective in lung cancer models with EGFR and ERBB2 mutations that are resistant to gefitinib. *Cancer Res*. 2007;67:11924-32.
18. Reckamp KL, Giaccone G, Camidge DR, Gadgeel SM, Khuri FR, Engelman JA, et al. A phase 2 trial of dacomitinib (PF-00299804), an oral, irreversible pan-HER (human epidermal growth factor receptor) inhibitor, in patients with advanced non-small cell lung cancer after failure of prior chemotherapy and erlotinib. *Cancer*. 2014;120:1145-54.
19. Miller VA, Hirsh V, Cadranel J, Chen YM, Park K, Kim SW, et al. Afatinib versus placebo for patients with advanced, metastatic non-small-cell lung cancer after failure of erlotinib, gefitinib, or both, and one or two lines of chemotherapy (LUX-Lung 1): a phase 2b/3 randomised trial. *Lancet Oncol*. 2012;13:528-38.
20. Camidge DR, Pao W, Sequist LV. Acquired resistance to TKIs in solid tumours: learning from lung cancer. *Nature reviews Clinical oncology*. 2014;11:473-81.
21. Zhou W, Ercan D, Chen L, Yun CH, Li D, Capelletti M, et al. Novel mutant-selective EGFR kinase inhibitors against EGFR T790M. *Nature*. 2009;462:1070-4.
22. Walter AO, Sjin RT, Haringsma HJ, Ohashi K, Sun J, Lee K, et al. Discovery of a mutant-selective covalent inhibitor of EGFR that overcomes T790M-mediated resistance in NSCLC. *Cancer Discov*. 2013;3:1404-15.
23. Cross DA, Ashton SE, Ghiorghiu S, Eberlein C, Nebhan CA, Spitzler PJ, et al. AZD9291, an irreversible EGFR TKI, overcomes T790M-mediated resistance to EGFR inhibitors in lung cancer. *Cancer Discov*. 2014;4:1046-61.
24. Kasibhatla S, Li J, Tompkins C, Vaillancourt M-T, Anderson J, Culazzo Pferdekamper A, et al. EGF816, a novel covalent inhibitor of mutant-selective epidermal growth factor receptor, overcomes T790M-mediated resistance in NSCLC. *Cancer Res*. 2014;74(19 Suppl).
25. Sequist LV, Soria J-C, Goldman JW, Wakelee HA, Gadgeel SM, Varga A, et al. Rociletinib in EGFR-mutated Non- Small-Cell Lung Cancer. *N Engl J Med*. 2015;372(18):1700-8.
26. Janne PA, Yang JC-H, Kim D-W, Planchard D, Ohe Y, Ramalingam SS, et al. AZD9291 in EGFR inhibitor-resistant non-small cell lung cancer. *N Engl J Med*. 2015;372:1689-99.
27. Ercan D, Xu C, Yanagita M, Monast CS, Pratilas CA, Montero J, et al. Reactivation of ERK signaling causes resistance to EGFR kinase inhibitors. *Cancer Discov*. 2012;2:934-47.
28. Cortot AB, Repellin CE, Shimamura T, Capelletti M, Zejnullahu K, Ercan D, et al. Resistance to irreversible EGF receptor tyrosine kinase inhibitors through a multistep mechanism involving the IGF1R pathway. *Cancer Res*. 2013;73:834-43.
29. Katayama R, Shaw AT, Khan TM, Mino-Kenudson M, Solomon BJ, Halmos B, et al. Mechanisms of acquired crizotinib resistance in ALK-rearranged lung Cancers. *Sci Transl Med*. 2012;4:120ra17.
30. Crystal AS, Shaw AT, Sequist LV, Friboulet L, Niederst MJ, Lockerman EL, et al. Patient-derived models of acquired resistance can identify effective drug combinations for cancer. *Science*. 2014;346:1480-6.

31. Guix M, Faber AC, Wang SE, Olivares MG, Song Y, Qu S, et al. Acquired resistance to EGFR tyrosine kinase inhibitors in cancer cells is mediated by loss of IGF-binding proteins. *J Clin Invest*. 2008;118:2609-19.
32. Misale S, Yaeger R, Hobor S, Scala E, Janakiraman M, Liska D, et al. Emergence of KRAS mutations and acquired resistance to anti-EGFR therapy in colorectal cancer. *Nature*. 2012;486:532-6.
33. Corcoran RB, Dias-Santagata D, Bergethon K, Iafrate AJ, Settleman J, Engelman JA. BRAF gene amplification can promote acquired resistance to MEK inhibitors in cancer cells harboring the BRAF V600E mutation. *Sci Signal*. 2010;3:ra84.
34. Lovly CM, McDonald NT, Chen H, Ortiz-Cuaran S, Heukamp LC, Yan Y, et al. Rationale for co-targeting IGF-1R and ALK in ALK fusion-positive lung cancer. *Nat Med*. 2014;20:1027-34.
35. Solca F, Dahl G, Zoephel A, Bader G, Sanderson M, Klein C, et al. Target binding properties and cellular activity of afatinib (BIBW 2992), an irreversible ErbB family blocker. *The Journal of pharmacology and experimental therapeutics*. 2012;343:342-50.
36. Godin-Heymann N, Ulkus L, Brannigan BW, McDermott U, Lamb J, Maheswaran S, et al. The T790M "gatekeeper" mutation in EGFR mediates resistance to low concentrations of an irreversible EGFR inhibitor. *Mol Cancer Ther*. 2008;7:874-9.
37. Lee HJ, Schaefer G, Heffron TP, Shao L, Ye X, Sideris S, et al. Noncovalent wild-type-sparing inhibitors of EGFR T790M. *Cancer Discov*. 2013;3:168-81.
38. Avizienyte E, Ward RA, Garner AP. Comparison of the EGFR resistance mutation profiles generated by EGFR-targeted tyrosine kinase inhibitors and the impact of drug combinations. *The Biochemical journal*. 2008;415:197-206.
39. Schwartz PA, Kuzmic P, Solowiej J, Bergqvist S, Bolanos B, Almaden C, et al. Covalent EGFR inhibitor analysis reveals importance of reversible interactions to potency and mechanisms of drug resistance. *Proc Natl Acad Sci U S A*. 2014;111:173-8.
40. Kim Y, Ko J, Cui Z, Abolhoda A, Ahn JS, Ou SH, et al. The EGFR T790M mutation in acquired resistance to an irreversible second-generation EGFR inhibitor. *Mol Cancer Ther*. 2012;11:784-91.
41. Liu X, Ory V, Chapman S, Yuan H, Albanese C, Kallakury B, et al. ROCK inhibitor and feeder cells induce the conditional reprogramming of epithelial cells. *The American journal of pathology*. 2012;180:599-607.
42. Dias-Santagata D, Akhavanfard S, David SS, Vernovsky K, Kuhlmann G, Boisvert SL, et al. Rapid targeted mutational analysis of human tumours: a clinical platform to guide personalized cancer medicine. *EMBO Mol Med*. 2010;2:146-58.

## Figure Legends

Figure 1 – A WZ4002-resistant cell line acquires a C797S mutation and maintains EGFR activity in the presence of TKI. A) MGH121 parental (pt) and MGH121 WZ4002 Resistant # 1 (Res # 1) cells were treated with the indicated concentrations of the 1<sup>st</sup> generation EGFR TKI gefitinib (GEF) or the 3<sup>rd</sup> generation EGFR TKI WZ4002 (WZ) for 72 hours. Cell viability was measured by CellTiter-Glo. Experiments were performed in quadruplicate and error bars depict standard error of the mean. B) MGH121 pt and Resistant # 1 cells were treated with the indicated concentrations of WZ4002 (nM) for 1 week and then stained with crystal violet. C) Lysates from MGH121 pt and MGH121 Resistant # 1 cells treated with DMSO or 1μM WZ4002 for 6 hours were probed with the indicated antibodies. D) Chromatograms depicting the acquired C797S mutation present in MGH121 Resistant # 1, but not MGH121 parental cells. The arrow is pointing to the mutated base (G is WT-Cys, C is mt-Ser).



Figure 2 – EGFR C797S confers resistance to all 2<sup>nd</sup> and 3<sup>rd</sup> generation EGFR TKIs. A) MGH121 pt (left) and Resistant # 1 (right) cells were treated with the indicated concentrations of EGFR TKIs for 72 hours. CellTiter Glo was used to measure cell viability. Experiments were carried out in triplicate and the error bars depict standard error of the mean. B,C) Lysates from MGH121 pt and MGH121 Res # 1 cells (B) and 293T cells overexpressing EGFR mutant constructs (C) treated with 1  $\mu$ M of the indicated TKIs except for AZD9291 (160nM) for 6 hours were probed with the indicated antibodies. D) Lysates from 121 pt and 121 pt stably overexpressing EGFR exon 19 del/T790M/C797S treated with 1  $\mu$ M of the indicated EGFR TKIs for 6 hours were probed with the indicated antibodies. E) The same cells were treated with the indicated doses of EGFR TKI for 72 hours. CellTiter Glo was used to measure cell viability. Experiments were completed in triplicate and error bars depict standard error of the mean. IC<sub>50</sub> values for each TKI and cell line are shown (bottom right).

Figure 3 – C797S located in cis or trans with T790M alters drug sensitivity. A) An Exon 20 PCR reaction was ligated into a TOPO vector and individual colonies representing a unique PCR product were sequenced. Left- representative chromatograph of the T790M and C797S mutations in cis. Right – quantification of allelic reads. B) Left - Western blot of 293T cells overexpressing the indicated *EGFR* mutant constructs and treated for 6 hours with the indicated drugs at a concentration of 1  $\mu$ M. Lysates were probed with the antibodies shown. Right – Schematic representation of the T790M and C797S alleles in cis and in trans. C) Western blot of MGH121 pt cells and MGH121 cells stably over-expressing the indicated *EGFR* mutant constructs were shown. Cells were treated as in B. Lysates were probed with the indicated antibodies. D) MGH121 cells stably expressing Exon 19 del/C797S were treated with the indicated concentrations of EGFR TKIs for 72 hours. GEF + WZ is 1 $\mu$ M of Gefitinib + the indicated doses of WZ4002. CellTiter Glo was used to measure cell viability. Experiments were carried out in triplicate and the error bars depict standard error of the mean.

Figure 4 – Cells resistant to third generation TKI in the first line setting via C797S mutation retain sensitivity to first generation TKI. A) Western blots of lysates from PC9 pt cells and PC9 cells stably overexpressing the indicated EGFR mutant constructs treated with the indicated TKIs at 1 $\mu$ M. B) PC9 parental or PC9 cells stably expressing Exon 19 del/C797S or Exon 19 del/T790M/C797S were treated with the indicated concentrations of EGFR TKIs for 72 hours. CellTiter Glo was used to measure cell viability. Experiments were carried out in triplicate and the error bars depict standard error of the mean. IC<sub>50</sub> values for each TKI for both cell lines are shown (bottom right).

Figure 5 – Schematic representation of EGFR resistance mutations in response to TKI treatment and sensitivity to subsequent therapies. Arrows indicate the treatment that the cancers have developed resistance to. Inhibitors shown in bold and underlined indicate the therapies that would potentially be effective in that cancer. Italics represent the mutations present in each case.

Figure 1

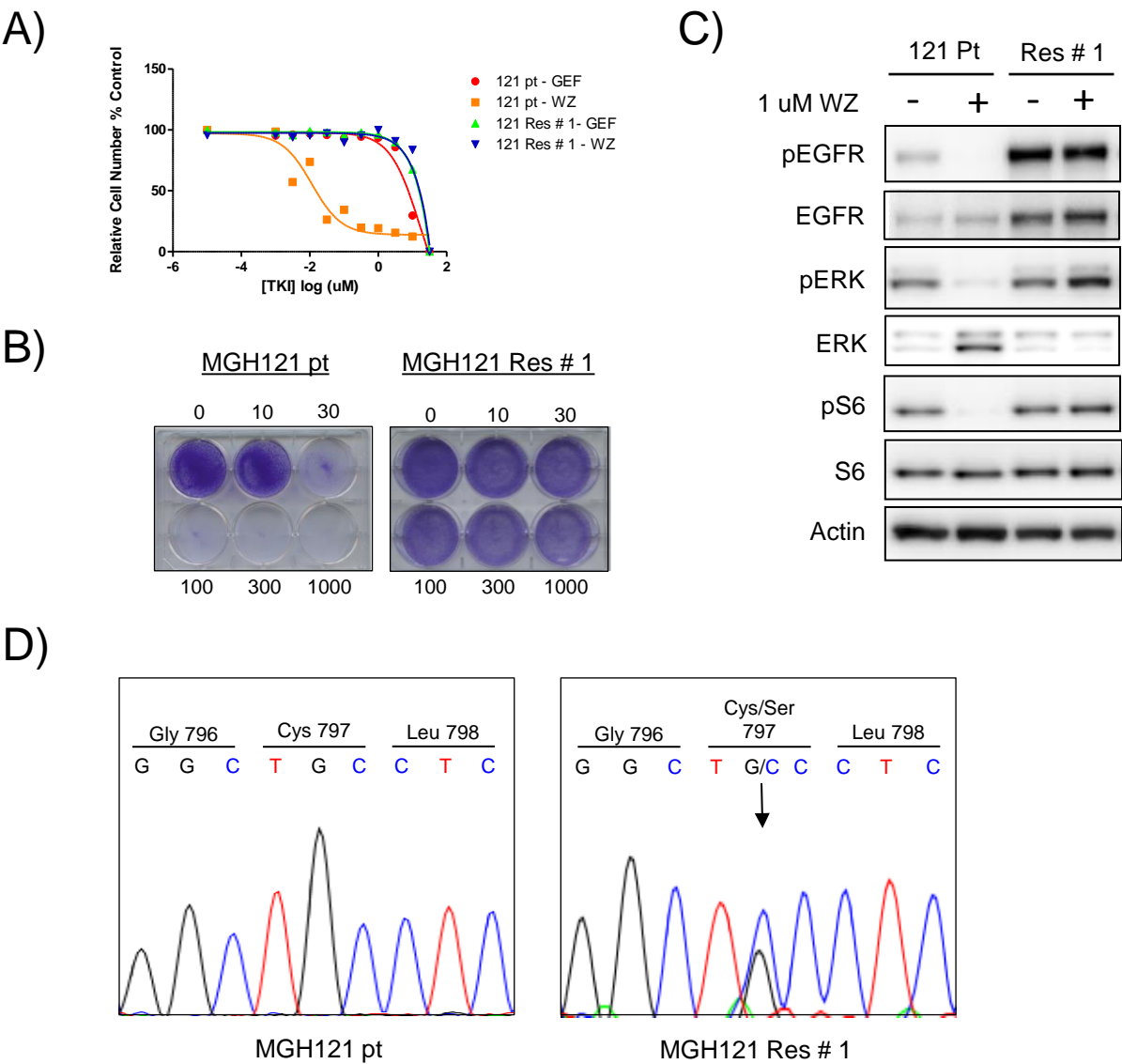


Figure 2

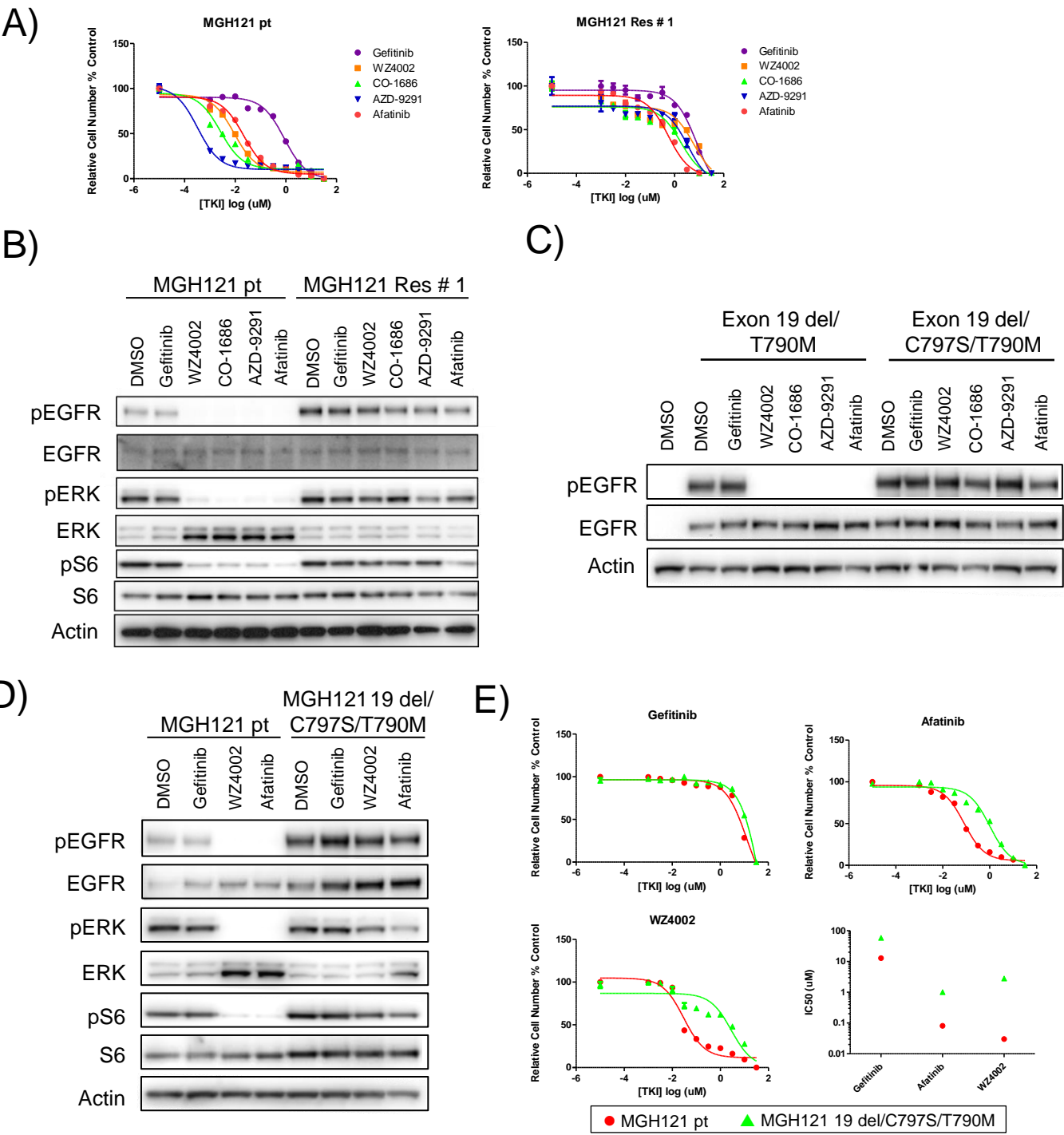
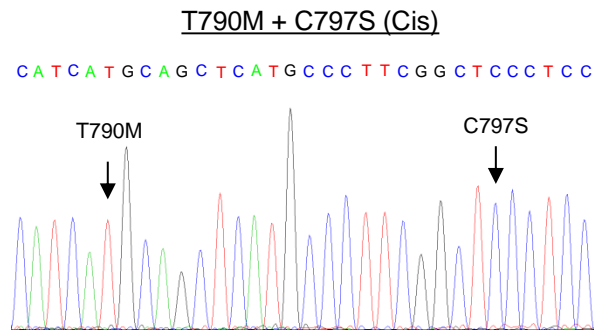


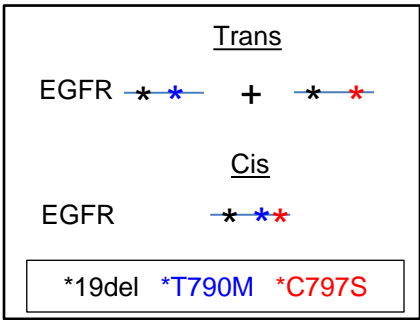
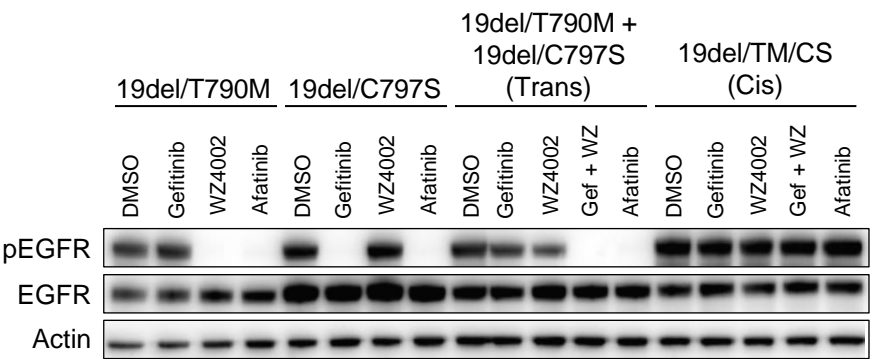
Figure 3

A)

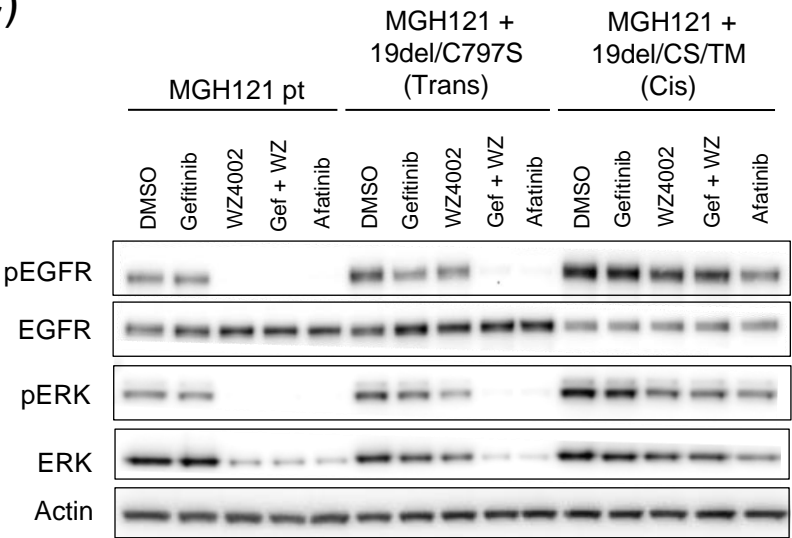


Allele	Reads (%)
WT/WT	18 (15%)
T790M/C797S	101 (85%)
T790M/WT	0 (0%)
WT/C797S	0 (0%)

B)



C)



D)

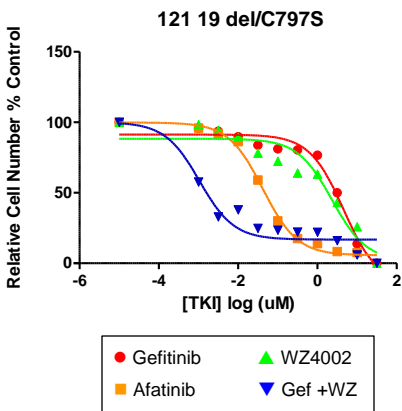
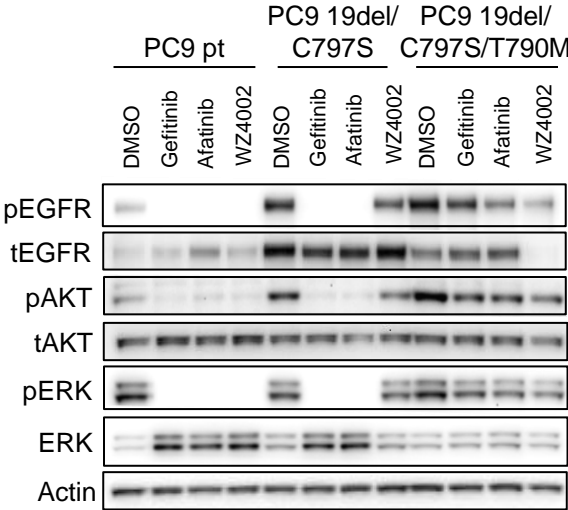


Figure 4

A)



B)

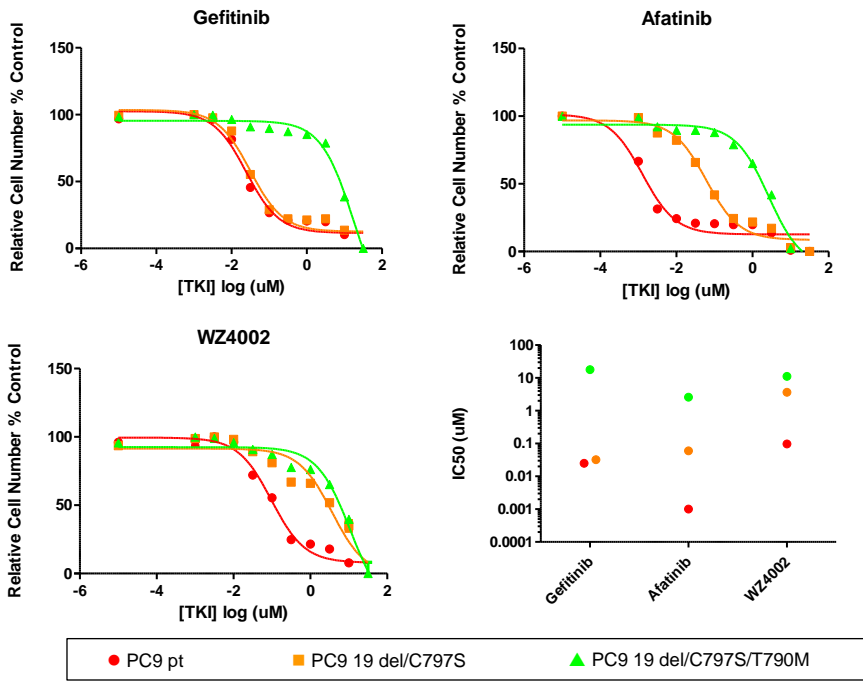
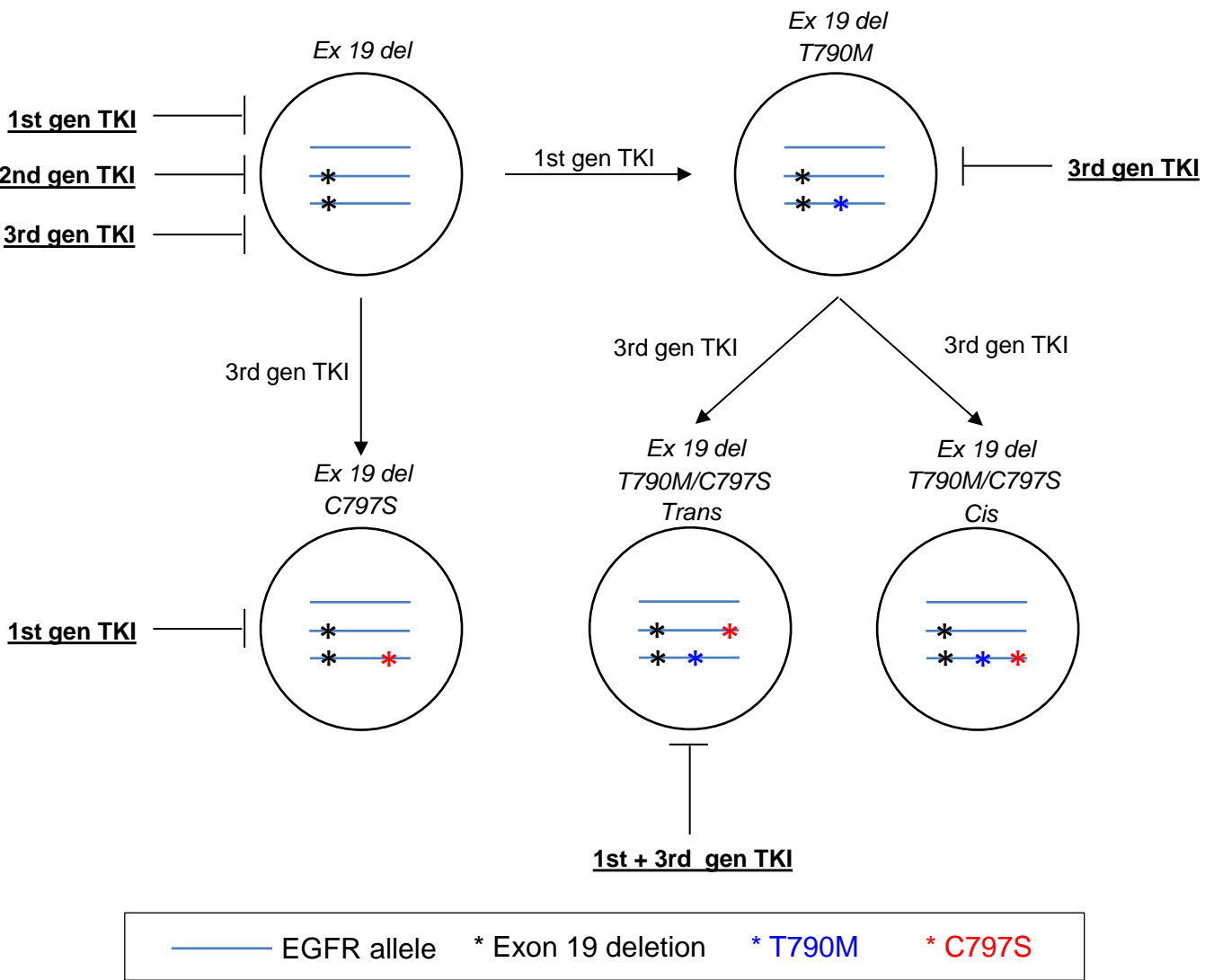


Figure 5



# Clinical Cancer Research

## The allelic context of the C797S mutation acquired upon treatment with third generation EGFR inhibitors impacts sensitivity to subsequent treatment strategies

Matthew J. Niederst, Haichuan Hu, Hillary E. Mulvey, et al.

*Clin Cancer Res* Published OnlineFirst May 11, 2015.

<b>Updated version</b>	Access the most recent version of this article at: doi: <a href="https://doi.org/10.1158/1078-0432.CCR-15-0560">10.1158/1078-0432.CCR-15-0560</a>
<b>Supplementary Material</b>	Access the most recent supplemental material at: <a href="http://clincancerres.aacrjournals.org/content/suppl/2015/05/12/1078-0432.CCR-15-0560.DC1.html">http://clincancerres.aacrjournals.org/content/suppl/2015/05/12/1078-0432.CCR-15-0560.DC1.html</a>
<b>Author Manuscript</b>	Author manuscripts have been peer reviewed and accepted for publication but have not yet been edited.

<b>E-mail alerts</b>	<a href="#">Sign up to receive free email-alerts</a> related to this article or journal.
<b>Reprints and Subscriptions</b>	To order reprints of this article or to subscribe to the journal, contact the AACR Publications Department at <a href="mailto:pubs@aacr.org">pubs@aacr.org</a> .
<b>Permissions</b>	To request permission to re-use all or part of this article, contact the AACR Publications Department at <a href="mailto:permissions@aacr.org">permissions@aacr.org</a> .