MEK inhibitor PD-0325901 overcomes resistance to PI3K/mTOR inhibitor PF-5212384 and potentiates anti-tumor effects in human head and neck squamous cell carcinoma

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Abstract

Purpose: Head and neck squamous cell carcinomas exhibit variable sensitivity to inhibitors of the PI3K(phosphoinositide 3-kinase)/mTOR(mammalian target of rapamycin) pathway, an important target of genomic alterations in this cancer type. The MEK(mitogen-activated protein kinase kinase)/ERK(extracellular signal-regulated kinase)/AP-1(activator protein 1) and NF-κB(Nuclear Factor-κB) pathways are also frequently co-activated, but their roles in resistance mechanisms to PI3K/mTOR inhibitors and as therapeutic targets in HNSCC are not well defined.

Experimental Design: We determined the IC₅₀s of dual PI3K/mTOR inhibitor PF-05212384 (PF-384) by XTT assays in 14 HNSCC lines with PI3K/Akt/mTOR cascade alterations. In two resistant models, we further characterized the molecular, cellular and \textit{in vivo} attributes and effects of combining PF-384 with MEK inhibitor PD-0325901 (PD-901).

Results: PF-384 IC₅₀s varied between 0.75nM-133nM in 14 HNSCC lines with overexpression or mutations of PIK3CA, and sensitivity correlated with increased phospho-AKT(T308/S473). In resistant UMSCC-1 and 46 models, PF-384 increased G₀/G₁ phase accumulation but weakly induced sub-G₀ cell death. PF-384 inhibited direct targets of PI3K-mTOR, but incompletely attenuated co-activated ERK and UMSCC-1 xenograft growth \textit{in vivo}. PD-901 strongly inhibited MEK/ERK targets, and the combination of PF-384 and PD-901 inhibited downstream NF-κB and AP-1 transactivation, and IL-8 and VEGF production \textit{in vitro}. PD-901 potently inhibited tumor growth alone and with PF384, enhanced anti-proliferative, apoptotic and anti-angiogenesis activity \textit{in vivo}.
Conclusions: PI3K/mTOR inhibitor PF-384 exhibits variable activity in a panel of HNSCC cell lines with differing PIK3CA expression and mutation status. MEK inhibitor PD-901 overcomes resistance and enhances anti-tumor effects observed with PF-384 \textit{in vivo}.

Translational Relevance: The PI3K/AKT/mTOR and MEK/ERK pathways are frequently altered cascades in head and neck cancers that promote co-activation of oncogenic transcription factors NF-κB and AP-1, tumorigenesis, and resistance against anticancer therapies. In this study, we show that dual PI3K/mTOR inhibitor PF-384 exhibits nanomolar range activity in a panel of 14 HNSCC lines with differing PIK3CA expression and mutation status, with sensitivity correlating with phospho-AKT(T308/S473). While PF-384 inhibited the PI3K/mTOR pathway, it incompletely attenuated ERK, AP-1, IL-8, and VEGF in less sensitive lines, implying a potential resistance mechanism. MEK inhibitor PD-901 potently suppressed MEK/ERK pathways and displayed strong anti-proliferative, apoptotic, anti-angiogenesis and anti-tumor activity in xenografts \textit{in vivo}. Our data suggest that MEK/ERK and PI3K/mTOR inhibition could be a more effective strategy to target this co-activated signal and transcriptional network, tumorigenesis, and resistance in HNSCC with various alterations activating PI3K or MEK.
**Introduction**

Head and neck squamous cell carcinoma (HNSCC) is the sixth most common cancer worldwide, and standard treatment with surgery or chemoradiation has significant morbidity, with 5-year survival of <50% (1). Molecularly targeted inhibitors for HNSCC gained interest following identification of agents targeting Epidermal Growth Factor Receptor (EGFR). However, when used either as single agents or in combination with radiation, these studies provided evidence of clinical activity in only ~10-15% of patients (2). Cumulative observations from mechanistic studies in HNSCC lines and proteomic and genomic studies in tumors suggest that multiple signaling molecules and pathways contribute to pathogenesis and a rationale for combination targeted therapy in HNSCC.

We identified several growth factor and inflammatory cytokine receptor tyrosine kinases (RTKs) and signal pathways forming a signal network that can promote growth and survival of HNSCC, and lead to resistance to EGFR and other targeted inhibitors. EGFR (3, 4), Hepatocyte Growth Factor Receptor (c-MET) (5, 6), and Tumor Necrosis Factor Receptor (TNFR) (7), are among the co-activators of the PI3K (Phosphoinositide 3-kinase)/Akt/mTOR (mammalian target of rapamycin) and MEK (Mitogen-activated protein kinase kinase)/ERK (extracellular signal-regulated kinase) signal cascades, that induce transcription factors NF-κB (nuclear factor-κB) and AP-1 (activator protein 1), respectively (4, 8-9). Supporting the importance of co-activation of these pathways, first generation PI3K and MEK antagonists inhibited EGF, HGF or TNF induced NF-κB, AP-1, target angiogenesis factor gene expression, and cell growth *in vitro* (4,6,8). Clinical trials with EGFR inhibitors or proteasome inhibition of NF-κB showed limited inhibition of PI3K-AKT-NF-κB or MEK-ERK signaling and clinical activity *in vivo* (3, 10).
Recent analysis by The Cancer Genome Atlas (TCGA) Network has identified genetic drivers that support PI3K and MEK as key common signal cascades and potential therapeutic targets for head and neck cancer (11). Overall, TCGA data shows >60% of HNSCC tumors harbor genomic alterations among various RTKs, PIK3CA, or HRAS, that converge on PI3K and MEK pathways. Among human papilloma virus negative (HPV-) HNSCC, ~30% display mutations or amplification of the PI3K catalytic subunit PIK3CA, while ~30% have activating alterations distributed among EGFR, ERBB2, FGFRs, EPHA2, IGFR and HRAS, which can potentially activate both PI3K and MEK pathways. In HPV+ HNSCC, nearly 60% of tumors harbor PIK3CA mutations and/or amplification.

Proteomic studies indicate levels of active phosphorylated AKT are highest in HPV-HNSCC (12). In recent preclinical studies with a dual PI3K-mTOR inhibitor PF-502, we observed anti-tumor activity in a subset of human HPV- HNSCC xenograft models which overexpress PIK3CA (13). Independent reports using other PIK3CA or PI3K/mTOR inhibitors suggested that HPV- or HPV+ HNSCC with PIK3CA mutations may exhibit greatest sensitivity (14-16). However, the potential basis for varying sensitivity and role for PI3K/mTOR and MEK inhibitors among the major subset of tumors with amplification and overexpression of PIK3CA has not yet been fully explored.

To examine the role of PI3K-mTOR and MEK inhibition in HNSCC, we selected two compounds to test in our models. PF-384(PKI-587/PF-5212384) and PD-901(PD-0325901/PF-0192513) are selective small molecule inhibitors of PI3K-mTOR and MEK, respectively, in early phase clinical trials, including one joint combination trial (NCT01347866). PF-384 is a reversible, ATP-competitive dual inhibitor of PI3Kα,
PI3Kγ and mTOR (17). PD-901 is a second generation, highly potent and specific non-ATP competitive inhibitor of MEK.

Here, we examined sensitivity to PI3K/mTOR inhibitor PF-384 in an expanded panel of 14 HNSCC lines, including 9 with a defined range of PIK3CA expression (13), and two with known H1047R activating mutations (14). We observed that sensitivity correlated with increased phospho-AKT(T308/S473). Conversely, the relative resistance to PF-384 correlated with lower phospho-AKT(T308/S473), but was not consistently dependent on expression or mutation of PIK3CA, implying a role for other pathway(s).

Among two HPV- HNSCC lines with PIK3CA overexpression that exhibited relative resistance to PF-384 in vitro and in vivo, we observed potent inhibition of PI3K-mTOR-mediated AKT and S6 kinase, but not MEK-mediated ERK phosphorylation. MEK inhibitor PD-901 potently inhibited ERK, tumor growth, and overcame the resistance to PI3K-mTOR inhibitor in vivo. The inhibitors blocked transactivation of AP-1 and NF-κB transcription factors, target angiogenesis factor reporter genes and proteins in vitro, and inhibited proliferative and angiogenesis markers in vivo. Together, our findings provide a rationale for incorporating MEK inhibitors to overcome resistance to PI3K-mTOR inhibitors in HNSCC with co-activation of these pathways.
Materials and Methods

Cell lines and culture

A panel of unique genotyped UM-SCC cell lines were obtained from Dr. T.E. Carey at the University of Michigan (Ann Arbor, MI, Supplemental Table 1), including nine previously shown to overexpress PI3KCA (p110α) protein (13). Genotyped HPV(+) UPCI, UD-SCC-2, and 93VU lines were kindly provided by Drs. Thomas E Carey with permission of originating scientists, and characteristics are as described (Supplemental Table 1). The origin of these HNSCC cell lines were authenticated by genotyping with 9 markers, and preserved in frozen stocks that were used within 3 months of culture as cited in Supplemental materials. Two additional HNSCC lines containing PIK3CA H1047R mutations (14) were generously provided by Dr. J.S. Gutkind at the National Institute of Dental and Craniofacial Research (Bethesda, MD).

Therapeutic agents

PF-5212384 (PF-384) and PD-0325901 (PD-901) were acquired through a Materials Transfer Agreement between Pfizer, Inc. (New London, CT) and the National Institute on Deafness and Other Communication Disorders (NIDCD) (Bethesda, MD). Preparations for use are described in Supplemental Methods.

XTT cell proliferation assay

XTT was performed according to manufacturer’s instructions (Roche #11465015001) and as described in Supplemental Methods. Half maximal inhibitory concentration (IC$_{50}$) was determined three days after treatment using the nonlinear four-parameter regression function in GraphPad Prism (La Jolla, CA).
Flow cytometric analysis of cell cycle

Flow cytometry was performed according to Cycletest Plus DNA Reagent Kit instructions (BD Biosciences #340242, San Jose, CA) and as described in Supplemental Methods. Data from 10,000 cells per treatment group and time point were analyzed using BD FACSDiva software (BD Biosciences).

Western blots

Specific antibodies, reagents, and methods are explained in Supplemental Methods. Densitometry was measured on ImageJ 1.45k software (National Institutes of Health, Bethesda, MD) by comparing drug treatment to untreated controls, and weighing phospho-proteins relative to whole proteins and actin loading controls.

Transient siRNA transfection

SMARTpool ON-TARGETplus PIK3CA (#L-003018) or Non-Targeting pool (#D-001810) siRNA (Thermo Scientific, Lafayette, CO) were complexed with Lipofectamine RNAiMAX transfection reagent (Invitrogen, Carlsbad, CA) in Opti-MEM reduced-serum media (Invitrogen) per manufacturer’s instructions. Specific reagent concentrations, plating densities and times are outlined in Supplemental Methods.

Real-time quantitative polymerase chain reaction

RNA isolation, cDNA synthesis and amplification were performed using the kits, primers, probes, and thermal cycle listed in Supplemental Methods. Relative gene expression was normalized to 18S endogenous control.

Luciferase gene reporters

Reporters, reagents, and conditions are described thoroughly in Supplemental methods. Data are normalized to cell density.
Enzyme-linked immunosorbent assay

Cytokines were measured using Quantikine IL-8 (#D8000C) and VEGF (#DVE00) Immunoassay kits from R&D Systems (Minneapolis, MN) following Supplemental Methods, and normalized to cell number.

HNSCC xenograft studies

All animal studies were carried out under protocols approved by the Animal Care and Use Committee, and in compliance with the Guide for the Care and Use of Laboratory Animals (National Research Council 2011). 20 gram, 4-6-week-old SCID/NCr-Balb/c mice were obtained from Frederick Cancer Research and Development Center (National Cancer Institute, Frederick, MD) and housed in a pathogen-free facility. UMSCC-1 or -46 cells were injected subcutaneously (s.c.) in flanks and animals were treated as described in Supplemental Methods.

Immunohistochemical analysis of tumors

Immunohistochemical staining and quantification were performed using a previously described method (13). Specific reagents and antibodies are listed in the Supplemental Methods.

Statistical analysis

In vitro experiments were performed in triplicate, with samples assayed in at least triplicate. Data are presented as the mean +/- standard deviation (SD). Significance was determined using the student’s t-test and $p$ values of $\leq 0.05$ were considered statistically significant. For tumor growth analysis, significance was determined using the student’s t-test and $p<0.05$. For survival analysis, the Gehan-Breslow-Wilcoxon test was used and significance was set to 0.05 using the Bonferroni method.
Results

Dual PI3K/mTOR inhibitor PF-384 variably attenuates cell growth and survival of HNSCC lines in vitro and displays limited anti-tumor activity in less sensitive models in vivo

For initial screening for sensitivity and resistance to PI3K/mTOR inhibitor PF-384, we assembled a panel of 14 HNSCC lines (Supplementary Table 1), that includes HPV- lines previously demonstrated to overexpress PIK3CA (UMSCC-1, 6, 9, 11A, 11B, 22A, 22B, 38, 46) (13), HPV+ line UM-SCC-47, and 2 HPV- lines which contain activating H1047R PIK3CA mutations (CAL-33 and Detroit-562) reported to exhibit enhanced sensitivity to PI3K/mTOR inhibitors (14). For ease of comparison, the XTT assay curves for 14 lines treated with concentrations of PF-384 between 1 nM to 5 μM in Fig. 1A are empirically separated into relatively high (0.75-10.2nM, left), intermediate (11.1-22.2nM; middle), or lower (48.5-133nM; right panel) drug IC50s. Overlap is observed between those with overexpression or mutations of PIK3CA. In an independent analysis comparing IC50s that included 11 HPV- and 8 HPV+ lines with PIK3CA amplification, HPV- lines were significantly more resistant to PF-384 when compared to HPV+ lines (Supplemental Figure 1, P=0.021).

We selected two of the less sensitive HPV- lines UMSCC-1 and 46, with similar overexpression of PIK3CA protein (13), to further characterize the limiting effects of PF-384 on G-S-M cell cycle phase and sub-G0 cell death using DNA fluorocytometry (Fig. 1B). Cells were treated at a concentration exceeding the IC50 of both cell lines (200 nM) and harvested at 24, 48, and 72 hours. At the time points studied, UMSCC-1 cells showed augmented G0-G1 accumulation, but a relatively small increase in sub-G0 DNA
fragmentation. In UMSCC-46, modest increases in the G_0-G_1 fraction were noted with treatment at 24-48 hours, and a delayed increase in sub-G_0 fraction was observed 48-72 hours after treatment. We next tested PF-384 as a single agent using a previously defined dosing schedule (17) in UMSCC-1 and 46 xenografts in vivo (Fig. 1C). UMSCC-1 showed a modest, but statistically significant reduction in tumor growth and prolonged survival. UMSCC-46 showed delayed tumor growth and prolonged survival, which did not reach statistical significance. Overall, tumor growth was minimally delayed and resumed growth parallel to controls during PF-384 treatment, and the difference in median survival was less than the 3 week course of treatment, consistent with relative resistance. Thus, in less sensitive HNSCC lines, PF-384 inhibited cell cycle progression but exhibited limited cytotoxic activity in vitro and anti-tumor activity in vivo.

Relationship of PF-384 sensitivity and resistance to AKT phosphorylation, and effects on PI3K/Akt/mTOR, MEK/ERK and IKK/NF-κB pathway signaling in resistant lines

As we previously quantified the constitutive expression of PIK3CA and phosphorylation of AKT(T308/S473) sites for PI3K-PDK1 and mTOR activation for a subset of this panel (13), we explored if sensitivity was associated with PIK3CA expression or AKT activation (Fig 2A-C). Sensitivity (lower IC50) for PF-384 was significantly correlated with higher phosphorylation of AKT(T308/S473) (Fig. 2A,B), but not with PIK3CA overexpression (Fig 2C), or H1047R mutation alone (Fig. 1A). These observations suggested that sensitivity to PF-384 correlates with signal phosphorylation
of AKT via PI3K/mTOR, while resistance may be associated with other pathway(s) in addition to PIK3CA expression or mutational status.

Since we had observed that HNSCC often display co-activation of PI3K/AKT/mTOR, and MEK/ERK signaling (4, 6, 8), we examined their activation and effects of PF-384 by Western blot in UMSCC-1 (Fig. 2D) and UMSCC-46 cells (Suppl. Fig. 2). PF-384 induced near complete, sustained inhibition of mTORC2 target p-Akt(S473), PI3K/PDK1 target p-Akt(T308), and mTORC1 targets p-S6(S240/244), and p-4E-BP1(S65) through 48 hours, indicating the limited sensitivity was not due to inadequate target inhibition. However, MEK target p-ERK1/2(T202/Y204) activation was only partially inhibited by PF-384 treatment. Because PI3K/AKT/mTOR have also been reported to modulate NF-κB via either Inhibitor-kappaB Kinase (IKK)-dependent p65 phosphorylation or co-factor dependent transactivation (18-24), we first examined the effects of PF-384 on IKK-dependent phosphorylation of serine 536-p65 RELA subunit of NF-κB, without or with inducer TNF-α (20 ng/ml)(Suppl. Fig. 3A,B). PF-384 partially inhibited TNF-α induced p-p65(S536) at early time points, but not at later time points.

We employed PIK3CA siRNA to examine specific effects on downstream molecules. Strong knockdown of PIK3CA was confirmed by RT-PCR and Western blot (Suppl. Fig. 4A,B). Knockdown of PIK3CA decreased pAKT(S473) and pAKT(T308), but had minimal effects on IKK-dependent phospho- or total p65. Together, these data indicate PF-384 potently inhibits direct PI3K/mTOR targets, but incompletely inhibits co-activated MEK-ERK and IKK-dependent NF-κB phosphorylation in HNSCC.
PF-384 inhibits transcription factor NF-κB and AP-1 reporter gene transactivation

PI3K/AKT/mTOR signaling has also been implicated in nuclear co-factor mediated transactivation of transcription factors NF-κB and AP-1 (4, 21), which co-regulate a variety of genes important in cancer cell proliferation, survival, inflammation and angiogenesis (25). To explore this, we investigated how PF-384 affected the regulation of transcription factor NF-κB and AP-1 reporter activity, with or without TNF-α stimulation in UMSCC-1 and -46 cells (Fig. 3A). The PI3K/mTOR inhibitor significantly suppressed basal and/or TNF-α-induced NF-κB and AP-1 at growth inhibitory concentrations between 50-200nM. PIK3CA specific siRNA knockdown alone partially inhibited NF-κB and AP-1 activities in both cell lines (Fig. 3B). These data indicate PI3K-mTOR inhibitor PF-384 significantly attenuates NF-κB and AP-1 mediated gene transactivation, and this is mediated at least in part by PIK3CA.

PF-384 modulates NF-κB/AP-1 and mTOR regulated inflammatory and angiogenic cytokine expression

To further examine the effects of PI3K/mTOR inhibition on known NF-κB/AP-1 transcriptional and mTOR translational targets important in angiogenesis and tumorigenesis of HNSCC (4, 8, 26-29), we next assessed the effects of PF-384 (200nM) on expression of IL-8 and VEGF angiogenesis factors as measured by ELISA, with or without TNF-α (20 ng/ml) stimulus (Fig. 4A). PF-384 strongly blocked IL-8 and VEGF expression. We further delineated effects of PF-384 and contribution of transcription factor activation for the IL-8 promoter by performing IL-8 luciferase reporter assays with mutated NF-κB, AP-1 and NF-IL6 (CEBPβ) binding sites (Fig. 4B). PF384 partially inhibited TNFα-induced IL-8 reporter activity in UM-SCC1, and NF-κB binding site
mutation most strongly reduced basal and TNF-\(\alpha\) induced reporter activity in both cell lines. Together, these data support the potential of PI3K-mTOR inhibitor PF-384 to suppress expression of angiogenesis factor IL-8 and VEGF, known targets of NF-\(\kappa\)B-dependent transcription and/or mTOR regulated protein translation.

**MEK inhibitor PD-901 potently inhibits ERK, NF-\(\kappa\)B, AP-1 and angiogenesis factors IL-8 and VEGF in vitro and tumorigenesis in vivo**

We hypothesized that co-activation of the MEK/ERK/AP-1 pathway observed (Fig. 2) could contribute to resistance to PI3K/mTOR inhibition in PF-384 resistant lines. PF-384 alone showed complete inhibition of direct targets p-Akt(T308) and p-S6(S240/244), but only weak inhibition of p-ERK1/2(T202/Y204), as before (Figure 5A). Conversely, PD-901 showed complete inhibition of p-ERK1/2, but did not inhibit p-Akt or p-S6. Combined treatment showed complete inhibition of all three proteins. We examined the effects of individual and combined treatment on NF-\(\kappa\)B and AP-1 transcription factor reporter gene activity (Fig. 5B), and downstream angiogenesis factor expression (Fig. 5C). Individual or combined treatment, with or without TNF-\(\alpha\), showed both PF-384 and PD901 reduced NF-\(\kappa\)B and AP-1 activity, and expression of angiogenesis factors IL-8 and VEGF. These data suggest that PF-384 and PD-901 and their targets both modulate activity of transcription factors and targets implicated in cell growth, survival, angiogenesis, and tumorigenesis.

**Effects of PF-384 and PD-901 on tumorigenesis in vivo**

We tested the effects of PF-384 and PD-901 on tumor growth and survival in vivo individually and in combination in the UMSCC-1 xenograft model (Fig. 5D). Tumor bearing mice were divided into four groups, vehicle control, 10 mg/kg PF-384 Q4D, 1.5
mg/kg PD-901 QD, or the combination for a single 21 day cycle of treatment. Notably, PD-901 and the combination potently suppressed tumor growth in this PF-384 resistant model. While all three drug treated arms showed statistically significant delayed tumor growth (p<0.05) until day 25, the PD-901 and combination groups remained significant until day 35. Compared to control, all three treatment arms also showed a statistically significant survival advantage, with the longest survival in the combination group. Tumor growth in PD901 only and combination groups eventually caught up with other groups with similar survival by day 55. These observations are consistent with the effects of PD901 and the combination being tumoristatic, with the implication that added cycles of treatment may be required to evaluate the durability of efficacy in clinical trials. Additionally, mice treated with PF-384, but not PD901, showed lack of weight gain as compared to controls (Suppl. Fig. 5), consistent with PI3K-mTOR inhibitory effects on metabolism. No significant toxicities were observed in any treated groups.

To examine the effects of PF-384 and PD-901 treatment on PI3K/Akt/mTOR and MEK/ERK targets, proliferation (Ki-67), apoptosis (TUNEL), and vessel density (CD31), we performed immunostaining and determined histoscores for these markers (30) in UMSCC-1 tumors isolated from additional animals (Fig. 6A-C, Suppl. Fig. 6). PF-384 treated tumor sections showed significantly decreased staining of direct PI3K and mTOR targets p-Akt(S473), p-Akt(T308), and weaker inhibition of p-ERK1/2 and p-S6(S240/244). PD-901 treated tumor sections showed reduced staining of p-ERK1/2 and lesser reduction of p-S6. Combination treatment most potently reduced staining of PI3K/mTOR targets and p-S6. Proliferation marker Ki-67 was reduced in all three conditions, with greatest inhibition in the combination group. Apoptosis (TUNEL)
staining was significantly increased in all treatment groups, with greatest increase in PD-901 or combination groups. Vessel density (CD31) and proangiogenic factor IL-8 was most significantly reduced with PD-901 and combination treatment. (Fig. 6C). Together, these findings demonstrate significant in vivo anti-tumor activity of PD-901 and its role in modulating MEK and corresponding pharmacodynamic markers in an HNSCC model exhibiting lower sensitivity to PI3K-mTOR inhibitor PF-384.
Discussion

Previously we showed that a subset of HPV- HNSCC models overexpressing PIK3CA were sensitive to an earlier generation dual PI3K-mTOR inhibitor, PF-502, \textit{in vitro} and \textit{in vivo} (13). Subsequent studies of HNSCC panels with defined mutant lines suggest HPV- and HPV+ tumors with activating PI3KCA mutations may be more sensitive to other PI3K and PI3K-mTOR agents (14-16). Here we found that a panel that includes PIK3CA overexpressing and H1047R PIK3CA mutant HPV- HNSCC lines, displays an overlapping range of sensitivity and resistance to dual PI3K-mTOR inhibitor PF-384 (Fig. 1), and relatively greater overall resistance when compared to HPV+ lines \textit{in vitro} (Supplemental Fig. 1). Higher sensitivity (lower IC50s) among HPV- HNSCCs overexpressing PIK3CA was correlated with phospho-AKT(T308 and S473), consistent with activation by signaling via PI3K-PDK1 and mTOR, respectively (Fig. 2A,B). As AKT activation has been associated with sensitivity to PI3K or mTOR inhibitors in other types of tumors (31-36), p-AKT may warrant investigation as a selective and pharmacodynamic biomarker for PI3K-mTOR inhibitors in future clinical studies. By contrast, PF-384 sensitivity was not correlated with expression or mutation of PIK3CA alone (Fig. 2C, Fig. 1A). The inverse relationship between resistance (higher IC50) and lower p-AKT, suggested that co-activation of other pathway(s) in addition to PI3K-AKT signaling could contribute to differences in sensitivity observed.

In depth study of two HPV- lines that displayed relative resistance \textit{in vitro} also showed limited response to PF-384 \textit{in vivo}, despite similar overexpression of PIK3CA (13). Limited response was not due to lack of target activity, as PF-384 potently blocked PI3K-AKT-mTOR signal and downstream functional NF-κB transactivation. However, it
incompletely inhibited MEK-ERK signal phosphorylation, which we previously showed to be frequently co-activated in HNSCC (8). Targeting MEK with PD-901 alone potently inhibited ERK signaling and tumor growth, and overcame the resistance when given together with PF-384 in vivo. Inhibition of MEK with PI3K/mTOR further inhibited p-AKT, pS6 as well as p-ERK, cell proliferation, survival, and angiogenesis in vivo (Fig 6). These observations support a model whereby co-activation and cross talk between PI3K-mTOR and MEK-ERK contribute to cell proliferation, survival, target transcription factor activity and expression of angiogenesis factors IL-8 and VEGF, angiogenesis, and tumorigenesis (Suppl. Fig. 6).

It is well accepted that the RTK-RAS and PI3K/Akt/mTOR axes promote cell survival, growth and metabolism (Suppl. Fig. 7). EGFR, other RTKs, and RAS implicated in HNSCC by TCGA and functional studies can trigger phosphorylation and activation of PI3K, which leads to activation of AKT and eventually mTORC1 through negative inhibition of TSC1/2 and Rheb (10). MEK/ERK crosstalk with the PI3K/mTOR pathway has also been reported to occur via concomitant inhibition of TSC1/2, which inhibit mTOR (Suppl. Fig. 7)(37). Thus MEK/ERK co-activation may enhance activation of mTOR and its downstream effectors, ribosomal protein S6 and translation repressor 4E-BP1, to integrate the function of ERK and Akt/mTOR signaling in transcription and translation in tumors (38). Our data showing that addition of PD901 potentiated the inhibitory effects of PF-384 on p-AKT (T308/S473) and p-S6 in tumors in vivo (Fig. 6A) suggest that the mechanisms of cross-talk between MEK-ERK and PI3K-mTOR warrant further investigation in HNSCC.
Recent studies have emphasized that several HNSCC lines with activating mutations of PIK3CA show greater sensitivity to various PI3Kor PI3K-mTOR inhibitors (14-16). In this study we explored mechanisms whereby HNSCC tumors evade molecular therapies targeting these pathways in models with wild-type PIK3CA and RAS (H. Cheng, unpublished data), which represent the majority of HNSCC tumors (11). The efficacy of combined MEK and PI3K/mTOR treatment in other studies conducted on adenocarcinoma of the colon (39, 43) and lung (40-42) is consistent with frequent alteration of RAS/RAF in those cancers. Considering much of the literature regarding PI3K and MEK combination therapy uses RAS or PIK3CA mutant models, the mechanisms of monotherapy resistance and efficacy of combined therapy targeting these pathways need to be better characterized in HNSCC and cancers lacking PIK3CA or RAS mutation, as established in the present study and another in colon cancer (44).

While HPV- HNSCC exhibit a lower rate of PIK3CA mutation, they exhibit frequent amplification of several other RTKs, PIK3CA, and express higher levels of active AKT and its phosphorylated downstream targets (11, 12). Activation of AKT or ERK has been shown to predict resistance to standard HNSCC therapies such as cetuximab (45, 46) and radiation (47), which can be augmented with PF-384 treatment (48). Studies in other cancer types have shown higher basal p-Akt to modulate increased response to PI3K inhibition (31, 32) or mTOR inhibition (33-36), regardless of PIK3CA mutational status, which corroborate our findings in HNSCC. Additionally, the effectiveness of combined MEK and PI3K/mTOR inhibition in colorectal cancer reduction is not dependent on KRAS or PIK3CA mutational status (44). Thus, resistance to PI3K/mTOR inhibition through sustained MEK/ERK signaling, and resistance to
standard radio- or chemo- therapies due to elevated p-AKT, can be overcome with combined PI3K/mTOR and MEK inhibition in HPV- HNSCC lacking PIK3CA mutation but exhibiting PIK3CA amplification and p-AKT activation. The function of MEK-ERK signaling in HNSCC is likely to include tumor-microenvironment dependent effects on proliferation, apoptosis, angiogenesis and tumorigenesis in vivo (Fig. 5, 6).

Previously, we showed that serum factors IL-8 and VEGF linked to PI3K and MEK co-activation are elevated in serum of patients with HNSCC and useful biomarkers for predicting response and survival in patients with advanced oropharyngeal SCC treated with chemoradiation (26). These factors are under the transcriptional control of both NF-κB and AP-1 transcription factors (4), and serve to collectively regulate angiogenesis and lymphangiogenesis (29). Both the PI3K and ERK pathways contribute to expression of IL-8 and VEGF through input from NF-κB and AP-1, respectively (8). While the in vitro capacity of PF-384 to inhibit PI3K/mTOR signaling and NF-κB transactivation was observed, xenografts were relatively insensitive to the drug. Incomplete inhibition of ERK, AP-1, and IL-8 and angiogenesis were associated with treatment resistance, which was overcome by single agent or combination therapy with PD-901. The rationale for this combination is further supported by other recent studies on HNSCC biomarkers of resistance to PI3K inhibitors (15).

The mechanisms involved in PI3K/Akt/mTOR mediated NF-κB activation, which is a well-described mediator of inflammation and oncogenesis, are complex. In this study we establish the effects and contribution of PI3K/mTOR inhibition by PF-384 and PIK3CA siRNA on NF-κB reporter gene activation, confirming our earlier observation that PI3K inhibition blocks NF-κB transactivation (4). Further, E545K and H1047R
activating mutations of PIK3CA prevalent in HNSCC have been directly implicated in upregulating NF-κB-dependent gene expression in other models (21). Although classical IKK signaling is a well-described mediator of NF-κB nuclear translocation and phosphorylation, we observed limited and transient inhibition of classical IKK dependent RELA/p-p65(S536) phosphorylation by PF-384 or PIK3CA siRNA, suggesting the potent inhibition of NF-κB transactivation observed occurs as a result of dual PI3K/mTOR pathway restriction upon co-activating mechanism(s). Further downstream, Akt and mTOR have been reported to co-regulate IKK-NF-κB transcriptional machinery (18-24). AKT mediates phosphorylation of nuclear cofactors such as IKKα and CBP/p300, which can bind and co-regulate transactivation of transcription factors NF-κB, AP-1 and p53 transactivation (24, 49, 50). Signal regulated interaction of CBP/p300 with pro-survival transcription factors such as NF-κB and AP-1 can promote their co-activation, and limit its availability and accessibility to p53. This is supported by the co-reduction of NF-κB and AP-1 transcriptional activation upon treatment with PF-384, and our previous finding that another dual PI3K/mTOR inhibitor, PF-502, could inversely enhance p53 expression and activity in these cell lines (13). Additionally, MEK-ERK induced AP-1 often binds and co-regulates many NF-κB modulated genes. Thus, it is apparent that NF-κB and AP-1 co-activation can be triggered at any number of points along the GFR/RAS/PI3K/Akt/mTOR signaling route, underscoring the importance and rationale for inclusion of MEK and PI3K-mTOR inhibition in targeting HNSCC harboring co-activation of these signal pathways.
Disclosure of Potential Conflicts of Interest

C Van Waes is recipient of Pfizer pharmaceuticals under a Material Transfer Agreement with NIDCD, but otherwise holds no financial interests.

Authors’ Contributions

Conception and design: S. Mohan, R. Vander Broek, Z. Chen, C. Van Waes

Acquisition of data: S. Mohan, R. Vander Broek, S. Shah, D.F. Eytan, M. Pierce, S.G. Carlson, J.F. Coupar, Jialing Zhang


Writing, review and/or revision of the manuscript: S. Mohan, R. Vander Broek, Z. Chen, C. Van Waes

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Figure Legends:

Figure 1. PI3K/mTOR inhibitor PF-384 effects on cell growth and survival of HNSCC lines in vitro and anti-tumor activity in resistant lines in vivo

(A) 14 HNSCC cell lines were plated in 96-well plates at optimal densities of 2-5×10^3 cells/well in 6 replicates, and next day treated with serial concentrations of PF-384 (1, 10, 25, 50, 100, 250, 500, 1000, and 5000 nM) or 0.01% DMSO diluent in media as control. 72h post-treatment, cell density was measured by XTT assay and displayed as relatively sensitive (left), intermediate (middle), or resistant (right panel) to PF-384 based on IC_{50}. IC_{50} is presented as mean±SD. (B) Effects of PF-384 treatment on cell cycle and death in UMSCC-1 and UMSCC-46. Cells treated with 200nM PF-384 were harvested at 24, 48, and 72h post treatment. After propidium iodide staining, cells were analyzed by DNA cytofluorometry. (C) Effects of single agent PF-384 on UMSCC-1 and UMSCC-46 xenografts in vivo. 5×10^6 cells were implanted s.c. into the flanks of SCID/Ncr-Balb/c mice. Once tumors were palpable, mice were randomized into two treatment arms (vehicle control n=15 or 10 mg/kg PF-384 Q4D n=15) for a period of 21 days. Two-tailed t-tests were used to compare tumor size between the respective treatment and control groups. *p<0.05. Error bars: standard error of the mean (SEM). For survival analysis, survival was calculated either by day of death or sacrifice based on tumor size criteria (>2 cm in length or width). The Gehan-Breslow-Wilcoxon test was used and significance set to 0.05 using the Bonferroni method.

Figure 2. Relationship of PF-384 sensitivity and resistance to pAKT and effects on PI3K/mTOR and MAPK/ERK pathways in HNSCC. PF384 IC50 shows a significant
inverse correlation with (A) pAkt(T308) and (B) pAkt(S473), but not for (C) PIK3CA (p110α). Scatter plot of PF384 IC50 and basal protein intensity for pAKT(T308), pAkt(S473) (adjusted to total AKT and actin protein), and PIK3CA (adjusted to actin), quantified by western blot for 9 lines (13). Pearson correlation coefficient (r) and corresponding P values are indicated. Significant trend lines and 95% confidence intervals (gray areas) are shown for pAKT(T308) and pAKT(S473). (D) Western blot of the effects of PF-384 on PI3K/AKT/mTOR and MEK-ERK signaling in UM-SCC-1 (and 46; Suppl. Fig. 1). Cells were treated with 200nM PF-384 or 0.01% DMSO diluent in media as a control for 6, 12, 24 and 48h, and midway to collection, TNF-α (20 ng/mL) as an inducer or control diluent was added. Western blots and quantification were performed as described in methods.

**Figure 3. Effects of PF-384 and PIK3CA siRNA on transcription factor NF-κB and AP-1 reporter gene activity.** (A) UMSCC-1 and 46 cells were plated in 24-well plates and transfected with luciferase reporter plasmids for 5h the following day. The transfected cells were treated with 50, 100, or 200 nM PF-384 or 0.01% DMSO diluent in media as a control for 48h. TNF-α (20 ng/mL) was added 16h prior to cell collection. (B) Control and PIK3CA siRNA oligonucleotides were transfected into UMSCC-1 and 46 cells along with luciferase reporter plasmids for 5h, and collected 48h later. TNF-α (20 ng/mL) was added 16h prior to cell collection. Values represent averages of three independent experiments with their SD for each condition in triplicate. Two-tailed t-tests were used to compare differences between the respective treatments and control cells. *p<0.05. Error bars: SD.
Figure 4. PF-384 effects on IL-8 and VEGF pro-inflammatory and angiogenic cytokine expression and IL-8 reporter activity. (A) UMSCC-1 and 46 cells were treated with PF-384 for 24 or 48 hours, with TNF-α (20 ng/mL) added 16 hours prior to each collection of conditioned media. IL-8, and VEGF expression were measured by ELISA and adjusted to total cell count. (B) IL-8 luciferase plasmids containing wild-type or mutant κB, AP-1 or CEBP response element promoter sequences were transfected into UMSCC-1 and 46 cells for 5h, and collected 48h later. TNF-α (20 ng/mL) was added 16h prior to cell collection. Values represent averages of three independent experiments with their SD and each condition in triplicate. Two-tailed t-tests were used to compare differences between the respective treatments and control cells. *p<0.05. Error bars: SD.

Figure 5. MEK inhibitor PD-901 shows individual and combined activity with PI3K/mTOR inhibitor PF-384 in UMSCC-1 cells in vitro and in vivo. (A) PI3K and MEK pathway components were detected by Western blot analysis of whole cell lysates from UMSCC-1 cells harvested 6h after 200 nM PF-384, 100 nM PD-901, or both. Band intensity values were normalized to the corresponding untreated control and β-actin loading control. (B) UMSCC-1 cells were plated in 24-well plates and transfected with luciferase reporter plasmids for 5h the following day. The transfected cells were treated with 0.01% DMSO control, 200 nM PF-384, 100 nM PD-901, or combination for 48 hours. TNF-α (20 ng/mL) was added 16h prior to cell collection. (C) UMSCC-1 cells were treated with PF-384, PD-901, or in combination for 24h, and TNF-α (20 ng/mL) was added 16h prior to each collection of conditioned media. IL-8, and VEGF expression
were measured by ELISA and adjusted to total cell count. Values represent averages of three independent experiments with their SD and each condition in triplicate. Two-tailed t-tests were used to compare the respective treatments and control cells with *p<0.05. (D) Effects of PF-384 and PD-901 combined treatment on tumorigenesis and survival in UMSCC-1 xenografts. 5x10^6 UMSCC-1 cells were implanted s.c. into the right hind flanks of SCID/NCr-Balb/c mice. Tumors were palpable 12 days post-inoculation and mice were randomized into one of four treatment groups (vehicle control n=18, 10 mg/kg PF-384 Q4D n=18, 1.5 mg/kg PD-901 QD n=19, or Combination, n=19) and treated for a period of 21 days. *p<0.05. Error bars: SEM.

Figure 6. In vivo effects of PI3K/mTOR and MEK inhibition
(A) Effects of PF-384 and PD-901 on PI3K/Akt/mTOR and MEK/ERK signal phosphorylation in vivo. (B), (C) Ki-67 proliferation, CD31 vessel density, TUNEL apoptosis, and IL8 expression in UMSCC-1 xenograft models of HNSCC. Immunostaining was done on tumors harvested on day 22. 10 HPFs were quantified per condition using Aperio software. Staining histoscores and representative IHC staining shown for untreated, PF-384, PD-901, and combination treatment groups. Bars: 100µm. Relative human IL-8 gene expression in tumor tissues of different treatment groups by quantitative RT-PCR. Treated UMSCC-1 xenografts were homogenized and RNA was purified. Statistical analysis was done by t-test (*p<0.05, **p<0.01, ***p<0.001). Error bars: SD.
Fig 2

A  
\[ r = -0.69 \quad P = 0.039 \]

B  
\[ r = -0.73 \quad P = 0.025 \]

C  
\[ r = 0.3 \quad P = 0.43 \]

D

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**Fig 3**

A. Comparison of NF-κB and AP-1 luciferase activity in UMSCC-1 and UMSCC-46 cells treated with DMSO, PF384 (50 nM), PF384 (100 nM), and PF384 (200 nM).

B. Luciferase activity in UMSCC-46 cells treated with control siRNA or PIK3CA siRNA.

- **NF-κB**
  - Endogenous
  - TNFα stimulated

- **AP-1**
  - Endogenous
  - TNFα stimulated

*Significant difference compared to controls.
MEK inhibitor PD-0325901 overcomes resistance to PI3K/mTOR inhibitor PF-5212384 and potentiates anti-tumor effects in human head and neck squamous cell carcinoma


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