PI3K/mTOR Inhibitor PF-04691502 Antitumor Activity Is Enhanced with Induction of Wild-Type TP53 in Human Xenograft and Murine Knockout Models of Head and Neck Cancer

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Abstract

Purpose: Phosphoinositide 3-kinase (PI3K)/mammalian target of rapamycin (mTOR) pathway activation is often associated with altered expression or mutations of PIK3CA, TP53/p73, PTEN, and TGF-β receptors (TGFBR) in head and neck squamous cell carcinomas (HNSCC). However, little is known about how these alterations affect response to PI3K/mTOR–targeted agents.

Experimental Design: In this preclinical study, PI3K/Akt/mTOR signaling was characterized in nine HNSCC (UM-SCC) cell lines and human oral keratinocytes. We investigated the molecular and anticancer effects of dual PI3K/mTOR inhibitor PF-04691502(PF-502) in UM-SCC expressing PIK3CA with decreased wild-type TP53, mutant TP53/C0/C0 mutantTGFBR2, and in HNSCC of a conditional Pten/Tgfbr1 double knockout mouse model displaying PI3K/Akt/mTOR activation.

Results: UM-SCC showed increased PIK3CA expression and Akt/mTOR activation, and PF-502 inhibited PI3K/mTORC1/2 targets. In human HNSCC expressing PIK3CA and decreased wtTP53 and p73, PF-502 reciprocally enhanced TP53/p73 expression and growth inhibition, which was partially reversible by p53 inhibitor pifithrin-α. Most UM-SCC with wtTP53 exhibited a lower IC50 than those with mtTP53 status. PF-502 blocked growth in G0–G1 and increased apoptotic sub-G0 DNA. PF-502 suppressed tumorigenesis and showed combinatorial activity with radiation in a wild-type TP53 UM-SCC xenograft model. PF-502 also significantly delayed HNSCC tumorigenesis and prolonged survival of Pten/Tgfbr1-deficient mice. Significant inhibition of p-Akt, p-4EBP1, p-S6, and Ki67, as well as increased p53 and TUNEL were observed in tumor specimens.

Conclusions: PI3K-mTOR inhibition can enhance TP53/p73 expression and significantly inhibit tumor growth alone or when combined with radiation in HNSCC with wild-type TP53. PIK3CA, TP53/p73, PTEN, and TGF-β alterations are potential modifiers of response and merit investigation in future clinical trials with PI3K-mTOR inhibitors. Clin Cancer Res; 19(14); 1–12. ©2013 AACR.
PTEN expression is decreased in ~60%, and mutated in ~7% of HNSCC (9–11). We recently detected increased phospho-Akt concurrent with decrease in PTEN and TGFBR1 expression in 8 of 20 (40%) human HNSCC; in which we showed repression of wild-type TP53, PF-502 reciprocally enhanced TP53 expression and apoptosis, and showed significant therapeutic activity alone and in combination with radiation. PF-502 also showed antitumor activity in a Pten/Tgfbr1-deficient murine head and neck cancer model, but not in human HNSCC with mtTP53/TGFBR2. These findings provide evidence for activity of PI3K/mTOR inhibitor PF-502 in HNSCCs in which PI3K-Akt activation is driven by distinct underlying alterations and contributions to repression of TP53. Evaluation of PI3KCA as well as TP53 and TGFBR alterations prevalent in HNSCC may be important to include in future clinical trials to identify selective factors for the broader class of PI3K-mTOR inhibitors.

**Translational Relevance**

Although phosphoinositide 3-kinase (PI3K)/mammalian target of rapamycin (mTOR) activation is prevalent in cancers, we found that activity of PI3K/mTOR–targeted agents differed among HNSCC models displaying distinct molecular alterations affecting TP53 and TGF-β tumor suppressor function. Notably, in HNSCC in which we showed repression of wild-type TP53, PF-502 reciprocally enhanced TP53 expression and apoptosis, and showed significant therapeutic activity alone and in combination with radiation. PF-502 also showed antitumor activity in a Pten/Tgfbr1-deficient murine head and neck cancer model, but not in human HNSCC with mtTP53/TGFBR2. These findings provide evidence for activity of PI3K/mTOR inhibitor PF-502 in HNSCCs in which PI3K-Akt activation is driven by distinct underlying alterations and contributes to repression of TP53. Evaluation of PI3KCA as well as TP53 and TGFBR alterations prevalent in HNSCC may be important to include in future clinical trials to identify selective factors for the broader class of PI3K-mTOR inhibitors.
HNSCC are well characterized for status of TP53 and TGFBR tumor suppressor alterations (Supplementary Tables S2 and S3; refs. 14, 16, and 17). The UM-SCC cells were cultured in minimal essential medium and 10% fetal calf serum. Human oral keratinocytes (HOK) obtained from oral gingival mucosa from Lonza were used as a control cell line.

Reagents
PF-04691502 was provided by Pfizer though a Materials Transfer Agreement with the National Institute of Deafness and Other Communication Disorders (NIDCD), and described previously (32, 33). The drug was resuspended to a stock solution of 10 mmol/L in dimethyl sulfoxide (DMSO) for in vitro experiments and 2.35 mmol/L in 0.5% methylcellulose (Sigma Aldrich) to deliver 5 to 10 mg/kg for in vivo experiments. TP53 inhibitor Pifithrin (35) was from Sigma-Aldrich.

Western blot
Western blots were done as previously described (11, 16, 29), using whole cell lysates and antibodies as described in Supplementary Methods. The quantification of the protein expression detected by Western blots was done by protein densitometry with ImageJ 1.45 k software, and the calculation was done using a formula described in Supplementary Methods.

MTT/XTT cell-density assay and cell-cycle analysis by DNA flow cytometry
Cell density was evaluated using MTT or XTT assay as indicated, and cell-cycle effects were characterized by DNA flow cytometry as described previously (16, 18) and in Supplementary Methods.

HNSCC xenograft and radiation regrowth delay tumor models
All animal experiments were carried out under protocols approved by the Animal Care and Use Committee of the NIDCD or NCI, and were in compliance with the Guide for the Care and Use of Laboratory Animal Resource (1996) National Research Council. Four- to 6-week-old female BALB/c severe combined immunodeficient (SCID; for xenografts) or nu/nu mice (for radiation experiments) were obtained from Frederick Cancer Research and Development Center (National Cancer Institute) and housed in a specific pathogen-free animal facility. Mice were injected s.c. in flanks with 5 × 10⁶ UM-SCC 1 or 46 cells and treated 1 to 2 weeks later, as described in Supplementary Methods and Supplementary Fig. S5.

Tgfbr1/Pten 2cKO mouse model studies
The Tgfbr1/Pten 2cKO mice were generated from crosses between Tgfbr1 cKO mice (K14-CreER<sup>tam</sup>;Tgfbr1<sup>−/−</sup>) and Pten<sup>−/−</sup> mice, induced as recently reported (11), and treated as described in Supplementary Methods and Fig. S5.

Immunohistochemical analyses of tumors
Immunohistochemical staining (IHC) and quantifications of slides with tumor from control or PF-502–treated mice were done using a previously published method (11), and as described in Supplementary Methods.

Statistics
Statistical analyses used were as indicated in figure legends and Supplementary Methods.

Results
Differential expression and molecular effects of dual PI3K/mTOR inhibitor PF-502 on PI3K/Akt/mTOR pathway components and TP53/p73 in HNSCC cell lines
We examined the expression and phosphorylation of key PI3K/Akt/mTOR pathway proteins in a panel of 9 human HNSCC (UM-SCC) cell lines, which have been previously genotyped and also demonstrate alterations prevalent in HNSCC tumors, including EGFR and PI3K/Akt activation (5, 6), as well as inactivation or mutations of TP53/p73 and TGFBRs (refs. 14, 16–17; Supplementary Tables S1–S3). Expression and/or phosphorylation of several PI3K/Akt/mTOR pathway components were differentially increased in most of the UM-SCC lines when compared with control HOK (Fig. 1A) and normalized to β-actin and UM-SCC1. A marked increase in protein expression of the PI3K p110alpha catalytic subunit (PIK3CA), p-Akt (S473 and T308), p-S6 (S240/244), and p-4EBP1 (T37/46) was observed in two thirds of wtTP53 deficient (UM-SCC1–6) and most mutant (mt)TP53 (UM-SCC11A-46) lines. Thus, the majority of UM-SCC lines showed differentially increased expression and/or phosphorylation of several PI3K/Akt/mTOR pathway components, consistent with previous studies in HNSCC tumors (7, 8, 19).

To compare the molecular effects of the PI3K-mTOR inhibitor PF-502 in UM-SCC with different molecular alterations, UM-SCC lines 1 and 46 were selected for initial study (Fig. 1B). These lines showed increased expression of PIK3CA, p-Akt, and mTOR targets, but either express low levels of wtTP53 (UM-SCC1), or express mtTP53 and mtTGFBR2 tumor suppressor proteins (UM-SCC46), previously observed in HNSCC subsets (14, 16, 18, 36). Based on differing IC<sub>50</sub>s for UM-SCC1 and 46 of ~2 and 0.6 μmol/L, respectively (Fig. 2A and B), we selected an intermediate concentration of PF-502 of 1.25 μmol/L, which resulted in detectable inhibition of UM-SCC1 and was ~2× the IC<sub>50</sub> for UM-SCC46. Treatment of both UM-SCC cell lines with PF-502 strongly inhibited PI3K and TORC2 targets p-Akt (T308/S473), and mTORC1 targets p-4EBP1 (S65/T37/46 residues) and pS6 (S240/244) by 6 hours postadministration, with sustained inhibition of p-S6 or p-4EBP1 (S65) observed up to 24 hours postadministration (Fig. 1B). However, greater than baseline phosphorylation was seen for PI3K/PDK1 target p-Akt (T308) and mTORC2 target p-Akt (S473) in UM-SCC1 by 12 to 24 hours, whereas earlier rebound for mTORC1 target p-4EBP1 (T37/46) was observed in UM-SCC46. PF-502 treatment had no inhibitory effect on total PI3K p110α or Akt expression, consistent with its action as an inhibitor of kinase activity.
As we have previously found evidence for repression of TP53 and p73 expression and tumor suppressor function in HNSCC (16, 17), we examined if PI3K/mTOR inhibition modulated expression of these proteins (Fig. 1B). Interestingly, PF-502 treatment induced an increase in expression of TP53 up to 50-fold in the UM-SCC1 line expressing minimal detectable levels of wtTP53, whereas a lesser fold increase in TP53 was seen in the UM-SCC46 line with already elevated basal levels of mtTP53 between 6 and 24 hours. A moderate increase in p73 was also observed in both UM-SCC1 and 46 after PF-502 treatment. To confirm these findings and control for experimental variability, protein loading, cell density, or cell line variation, we conducted additional experiments (Supplementary Fig. S1). Reproducible inhibition of selected PI3K/mTOR targets and a clearly inducible expression of TP53/p73 proteins were observed in replicate as well as independent experiments with time/density-matched controls for UM-SCC1 and 46 (Supplementary Fig. S1A–S1D). In addition, inhibition of selected PI3K/mTOR targets and induced expression of TP53/p73 proteins were observed in an independent wtTP53 line UM-SCC6 expressing detectable TP53 and p73 (Supplementary Fig. S1E). These findings indicate that dual PI3K/mTOR inhibitor PF-502 had similar inhibitory effects on PI3K/mTOR signaling, while enhancing expression of TP53 and p73 expression in multiple UM-SCC lines with wtTP53 or mtTP53.

Dual PI3K/mTOR inhibitor PF-502 differentially modulates cell growth and survival of HNSCC in vitro

UM-SCC1 and 46 cell lines treated with increasing PF-502 concentrations between 25 nmol/L to 10 μmol/L over a 5-day MTT assay exhibited a dose-dependent decrease in cell density (Fig. 2A and B). UM-SCC1 had a higher IC50 value of ~2 μmol/L as compared with an IC50 of ~0.6 μmol/L for UM-SCC46. As we observed PF-502–modulated TP53, we examined an expanded panel of UM-SCCs, which included 5 wtTP53 and 6 mtTP53 lines (Supplementary Tables S1 and S2) for IC50s of PF-502 (Supplementary Fig. S2). For IC50s, most mtTP53 lines appeared to be relatively more resistant, except for two with IC50s overlapping those of wtTP53 lines, whereas wtTP53 line UM-SCC1 was a more resistant outlier by boxplot analysis.
PI3K/mTOR Inhibition Induces TP53 in HNSCC

PF-502 inhibitor effects on cell density of UM-SCC cell lines and partial rescue by TP53 inhibitor pifithrin-α. UM-SCC 1 (A) and UM-SCC46 (B) were treated with varying concentrations of PF-502 (25 nmol/L to 10 μmol/L PF-502), and the effect on cell density was assessed in 5-day MTT assay. Decreasing cell density was seen in both UM-SCC1 and UM-SCC46 with increasing PF-502 concentrations, with IC50 values of ~1.9 μmol/L and 600 nmol/L, respectively. C, boxplots of IC50 for 6 mtTP53 (red) and 5 wtTP53 lines (cyan; Supplementary Table S2). IC50 levels were significantly higher for most mtTP53 relative to wtTP53 cell lines (P = 0.049, robust least squares regression analysis [Supplementary Methods]). Each sample was assayed in 6 replicates, and data are presented as the mean for each concentration. The y-axis is log2 scaling, transformed. Dark horizontal lines represent the median, with the box representing the 25th and 75th percentiles. The whiskers indicate the lowest datum still within 1.5 interquartile range (IQR) of the lower quartile, and the highest datum still within 1.5 IQR of the upper quartile, and outliers represented by dots that are either 3 × IQR or more above the top box (third quartile) or 3 × IQR or more below the bottom box (first quartile). D, UM-SCC1 cells were treated with 0.05% DMSO, PI3K-mTOR inhibitor PF-502 (1 μmol/L), selective TP53 inhibitor pifithrin-α (10 μmol/L), or with a combination of pifithrin pretreatment for 5 hours before PF-502 exposure. Quantitative comparison of cell density by XTT assay at 48 hours (**, P ≤ 0.01; ****, P ≤ 0.0001). PF-502 reduced cell density and cell adherence, effects that were partially reversed by TP53 inhibitor pifithrin-α.

To further evaluate the effects of PF-502 on cell cycle and death, DNA cytfluorometric analysis of UM-SCC1 and 46 cells was compared after treatment with PF-502 at twice their established IC50 values (Fig. 3). UM-SCC1 cells treated with PF-502 (4 μmol/L) exhibited increased G0–G1 accumulation over 24 to 48 hours, and sub-G0 DNA over 24 to 72 hours, consistent with the G0–G1 growth arrest and cell death expected with the PI3K/Akt/mTOR signal inhibition, and increased TP53/p73 protein expression observed with PF-502 above. By contrast, treatment of UM-SCC 46 cells with 1.2 μmol/L PF-502 showed a lesser increase in G0–G1 and no further increase in the elevated sub-G0 fraction observed with late growth. Because the differences in DNA fraction could be related to lower concentration used for UM-SCC46, we also compared the effects after treating both at the same concentration of ~IC50 for UM-SCC1 (2 μmol/L). Under these conditions, PI3K/Akt/mTOR
inhibition still had a differentially greater effect on G_0–G_1 cell-cycle arrest in UM-SCC1 than 46, and similar enhancement of sub-G_0 DNA in both lines required ~3 × the IC_{50} for UM-SCC46 (Supplementary Fig. S4). Cell-cycle analysis conducted for additional wtTP53/TGFBR2 lines UM-SCC6 (IC_{50} ~ 0.2 μmol/L), UM-SCC9 (IC_{50} ~ 0.15 μmol/L), and mtTP53/wtTGFBR2 line UM-SCC38 (IC_{50} ~ 0.5 μmol/L) also showed PF-502–induced G_0–G_1 accumulation (Supplementary Fig. S4A). wtTP53 UM-SCC6 and 9 showed relatively higher baseline and PF-502 inducible sub-G_0 fraction by 24 hours, whereas PF-502–induced increase in sub-G_0 DNA was delayed until 48 hours in UM-SCC38 with mtTP53/wtTGFBR2 (Supplementary Fig. 4B). Together, the above findings suggest that TP53 status as well as other factors contribute to the sensitivity of UM-SCC to PF-502.

PF-502 differentially affects tumor growth and survival and delays tumor growth with radiation in a human HNSCC xenograft model with wtTP53

To evaluate the activity and tolerability of PF-502 in HNSCC in vivo, pilot dosage studies were done using the UM-SCC1 (wtTP53) and UM-SCC46 (mtTP53 and mtTGFBR2) as human HNSCC xenograft models. Tumor cells were implanted s.c. into the flank of SCID mice, and treatment was initiated beginning ~14 days after implantation when tumors were palpable. PF-502 (5, 7.5, and 10 mg/kg) or control vehicle were given via oral gavage for 21 consecutive days (see schema; Supplementary Fig. S5). After establishing 10 mg/kg of PF-502 as the most effective tolerated dose (data not shown), we conducted a larger trial (n ≥ 12 per group) in UM-SCC1 and UM-SCC46 xenograft mice, and the effects on tumor growth and survival were
compared (Fig. 4A, B). Although UM-SCC1 showed more rapid tumor growth than UM-SCC46 in vivo, PF-502 had a greater inhibitory effect on the tumor growth in the wtTP53 UM-SCC1 xenograft mouse model than in UM-SCC46 with mtTP53 and mtTGFBR2 (Fig. 4A). At the completion of treatment on day 21, the difference in tumor volume versus control was highly statistically significant ($P < 0.0001$) in the UM-SCC1 model and associated with an improvement in median survival of 10 days (Fig. 4B). By contrast, PF-502 treatment in UM-SCC46 xenograft mice exhibited a less potent antitumor effect (Fig. 4A) without significant improvement in survival (Fig. 4B).

In both HNSCC xenograft mouse models, tumor growth resumed after daily PF-502 treatment was withdrawn on day 21. This growth rate was relatively consistent with that seen in vehicle-treated control mice. In the UM-SCC46 xenograft model, this tumor growth increase after treatment cessation led to equalization of tumor volume by about day 32, accounting for the lack of effect on survival. Regarding the drug toxicity, 10 mg/kg of PF-502 was well tolerated, with all mice having normal body conditioning scores of 3. Although weight increase was delayed in UM-SCC1 as compared with UM-SCC46 xenograft mice treated with PF-502, this approximated the difference in tumor volume and mass of 2.25 g between treated and control mice for days 18 to 21 (Supplementary Fig. 6A and B).

As PF-502–enhanced expression of wtTP53 and p73 in UM-SCC1, we examined if combining PF-502 with DNA-damaging therapy with radiation further delayed tumor regrowth. As shown in Fig. 4C, 5 daily doses of PF-502 or 15 Gy single-dose radiation inhibited tumor growth compared with control. The combination of PF-502 and radiation further delayed tumor growth. The times for tumors to reach 4 times the initially measured tumor volume relative to the control for PF-502 alone, 15 Gy, and PF-502 plus 15 Gy were 23.2 ($P = 0.20$), 23.6 ($P = 0.04$), and 29.4 ($P = 0.02$) days, respectively.

PF-502 delays HNSCC tumor development and growth and improves survival in Pten/Tgfbr1 2cKO mice

Decreased PTEN and TGFBR1 has been detected in ~40% of human HNSCC and implicated in PI3K/Akt/mTOR
activation and tumor development (10–12). As we recently established that increased PI3K-Akt-mTOR activation and HNSCC tumorigenesis with 100% penetrance is a consequence in \( \text{Pten/Tgfbr1}^{2cKO} \) mice (11), we examined the potential of PF-502 to inhibit development and growth of HNSCC in this defined transgenic mouse model. After a pilot dosage escalation study, PF-502, 10 mg/kg, for 3 weeks, was found to be well tolerated and without significant weight loss or toxicity for up to 6 months (data not shown). Treatment of larger groups of \( \text{Pten/Tgfbr1}^{2cKO} \) mice (n > 18) with PF-502 was then initiated 4 weeks after deletion of \( \text{Pten} \) and \( \text{Tgfbr1} \) via tamoxifen-induced Cre expression and 2 weeks before full development of HNSCC, when ~50% of mice exhibited small visible lesions. 2cKO mice were treated with 10 mg/kg of PF-502 for 21 consecutive days by oral gavage. PF-502–treated 2cKO mice exhibited a significant decrease in development and growth of external head and neck and oral tongue tumors (Fig. 5A–D; \( P < 0.05 \)), as compared with control mice. Delayed tumor development and growth were seen after treatment cessation, requiring ~20 days after treatment cessation before reaching similar tumor volumes as controls (Fig. 5D). This PF-502–mediated tumor growth delay in 2cKO mice corresponded to an improvement in median survival of ~20 days, from a median survival of ~40 days in control mice to >60 days in PF-502–treated mice (Fig. 5E). PF-502 was well tolerated, without significant weight loss in treated versus control mice (Supplementary Fig. 6C).

**PF-502 inhibited PI3K/Akt/mTOR and Ki-67 and increased TP53 and TUNEL staining in xenograft and 2cKO models in vivo**

Effects of PF-502 treatment for 21 days on PI3K/Akt/mTOR, TP53/p73, and related proliferation (Ki67) and apoptosis (TUNEL) markers were examined by immunostaining in HNSCC tumors from UM-SCC1 and 46 xenografts and \( \text{Pten/Tgfbr1}^{2cKO} \) mice (Fig. 6A). Tumor immunostaining was quantified by histoscores (Fig. 6B). PF-502 treatment for 21 days significantly decreased PI3K/Akt/mTOR...
pathway signaling as measured by decreased staining of p-Akt (S473) and downstream p-4EBP1 (T37/46) and p-S6 (S240/244) in tumor specimens from all three models (Fig. 6). Conversely, TP53 was significantly increased in tumors from wtTP53 UM-SCC1 and mtTP53 UM-SCC46 xenografts but did not reach significance in 2cKO mice. p73 staining was slightly increased but also did not reach statistical significance in the three tumor models. There was a statistically significant decrease in proliferation (Ki67) and an increase in apoptosis (TUNEL) marker staining in tumor specimens from all three models, with greater relative increase in TP53 and TUNEL staining observed in UM-SCC1 with wtTP53. TP53 inducible cell-cycle-dependent kinase inhibitor p21Cip1 gene expression was increased in wtTP53 UM-SCC1 but not in mtTP53 UM-SCC46 tumors, providing further evidence for functional activation of TP53 (Supplementary Fig. S7).

Discussion

Here, we show that PI3K/mTOR antagonist PF-04691502 has antitumor activity in PIK3CA-overexpressing/TP53-deficient human and Pten/Tgfbr1-deficient murine head and neck cancer models, which reflect alterations found concurrently with PI3K/Akt/mTOR activation in human HNSCC subsets. Notably, in HNSCC from the subset in which we previously showed decreased wtTP53/p73 expression (16, 17), PF-502 inhibited PI3K/Akt/mTOR signaling and reciprocally enhanced TP53 and TUNEL expression in UM-SCC1 xenografts. The increase in p73 in PF-502-treated mice did not reach significance (P < 0.05).
observed in human UM-SCC46 with PIK3CA overexpression, Akt/mTOR activation, but mutations of both TP53 and TGFBR2 (14, 16). Our findings comparing IC_{50} of a wider panel of UM-SCC in vitro suggest that TP53 status as well as other factors contribute to the sensitivity of UM-SCC to PF-502. Preliminary findings from the The Cancer Genome Atlas have detected amplifications or putative activating mutations in PIK3CA in ~30% of 279 HNSCC tumors, which overlap with wild-type and mutant TP53 subsets, and other less prevalent candidate gene alterations (36). Together, these observations underscore the importance of evaluating molecular and antitumor effects of PI3K/Akt/mTOR pathway targeted therapy in experimental models and clinical subsets with different genetic and molecular alterations of biologic relevance in HNSCC.

The frequent activation of PI3K/Akt/mTOR pathway by upstream receptor tyrosine kinases or intrinsic alterations (3–12) provides an important rationale for investigation of dual PI3K/mTOR inhibitors in HNSCC. The PI3K/Akt/mTOR signaling pathway is activated in most UM-SCC lines and involves increased expression of the PIK3CA (p110alpha) catalytic subunit, p-Akt, p-mTOR, p-4EBP1, and p-S6 (Fig. 1A; Supplementary Fig. S8), as often observed in human tumors (7, 19). Treatment with PF-502 blocked downstream targets of PI3K and mTORC2 (pAkt T308/S473, mTORC1 [p-S6(S240/244)], and p-4EBP1[Thr37/46]), consistent with dual PI3K/mTORC1/2 inhibitor activity. However, the duration of blockade was limited for p-Akt (S473 and T308) and some other downstream components in UM-SCC1 and 46 by 12 to 24 hours, as was also observed using lower concentrations of PF-502 in other tumor types in vitro and in vivo (33).

Reactivation of PI3K/Akt with mTOR inhibition has been reported to result from loss of feedback inhibitory loop involving p-S6 and IRS-1 (Supplementary Fig. S8; ref. 2). The greater than baseline increase in p-S6 (S473 and T308) by 24 hours for UM-SCC1 (Fig. 1B) could potentially explain the requirement for markedly higher concentrations of PF-502 to inhibit proliferation of UM-SCC1 relative to UM-SCC 46 in vitro (Fig. 2A and B). However, these p-Akt markers were similarly inhibited in all three tumor models in mice receiving 10 mg/kg every 24 hours in vivo, indicating that steady-state concentrations of PF-502 were adequate to inhibit p-Akt and p-S6 in vivo. A phase I clinical trial with daily PF-502 for recurrent cancers has recently been completed, and p-Akt as a candidate marker of PF-502 activity is planned (R. Millham; personal communication; Pfizer). Preliminary analysis of this phase I clinical trial provides evidence for clinical activity, with prolonged stable disease in 12 of 36 (33%) patients (R. Millham; personal communication; Pfizer), similar to tumoristatic effects we observed in UM-SCC1 and 2cKO HNSCC mouse model with PF-502 inhibiting p-Akt and p-S6 and significantly inhibited tumor development and prolonged survival. These effects were also

In this regard, the reciprocal enhancement in expression of TP53/p73 tumor suppressor proteins and the apparent relationship between TP53 status and IC_{50} for the majority of UM-SCC lines with blockade of the PI3K/Akt/mTOR pathway are important findings of this study. Increases in TP53 and p73 were detected in wtTP53 UM-SCC1 and UM-SCC 6 lines in vitro, and mtTP53 and p73 were also further increased in UM-SCC46. Pifithrin partially attenuated PF-502–induced growth inhibition in wtTP53 line UM-SCC1, consistent with contribution of TP53 to growth inhibition. We further show that UM-SCC1 with inducible wtTP53 exhibits greater G_{0}/G_{1} growth arrest, and that concentrations ~3 x IC_{50} for UM-SCC46 with mtTP53 are required to induce a comparable increase in sub-G_{0} DNA (Fig. 3 and Supplementary Fig. S4). Furthermore, wtTP53 UM-SCC6 and 9 showed relatively higher baseline and PF-502 inducible sub-G_{0} fraction by 24 hours, whereas PF-502 did not induce increased sub-G_{0} DNA until 48 hours in UM-SCC38 with mtTP53/wtTGFBR2 (Supplementary Fig. S4, right panels). Together, these data suggest that TP53 status as well as other factors, such as PI3KCA mutations, contribute to the sensitivity of HNSCC to PI3K/mTOR inhibitors (37).

Similar effects of PF-502 associated with genotype were observed in vivo (Fig. 6). We found that UM-SCC1, which is wtTP53 genotype and exhibits greater differential induction of TP53 and growth arrest than mtTP53/TGFBR2 line UM-SCC46, shows a greater reduction in proliferation (Ki67) and induction of apoptosis (TUNEL), consistent with the higher sensitivity to tumor inhibition observed. Furthermore, PF-502 induced TP53 target and growth arrest gene p21 in UM-SCC1 tumors, which was not observed in mtTP53 line UM-SCC46 (Supplementary Fig. S7). These data support that wtTP53 genotype and function contribute to the difference observed. The capability of PI3K/mTOR inhibition to enhance TP53 expression and effects when combined with radiation has broader implications for combination with radiation or chemotherapies that enhance the TP53 DNA-damage response.

We previously showed that wtTP53 mRNA and protein expression is repressed in UM-SCC1 and a subset of HNSCC, and that the repression of TP53 mRNA, protein, and TP53-dependent growth arrest and cytotoxicity was reversible by treatment with quinacrine (16), but its target of action was unclear. Subsequent studies suggested that quinacrine enhances TP53 reexpression via an Akt-dependent mechanism (32). We also reported that Akt mediates phosphorylation and cytoplasmic inactivation of p73 cofactor YAP in the same subset, which is important in p73 stabilization and transcription (18). Recently, mTOR inhibitor rapamycin was implicated in modulating p73 genes involved in mesenchymal differentiation and tumorigenesis in rhabdomyosarcoma (38). Our current results showing that a dual PI3K/mTOR inhibitor increases TP53, and to a lesser extent, p73 expression, further support the hypothesis that this pathway contributes to inactivation of TP53/p73 in this HNSCC subset.

Our 2cKO transgenic mouse model enabled evaluation of the effect of PF-502 on HNSCC with defined genetic alterations in PTEN and TGF-β signaling, which we have shown enhance PI3K/Akt activation (11). Treatment of the novel Tgbr1/Pten 2cKO HNSCC mouse model with PF-502 inhibited p-Akt and p-S6 and significantly inhibited tumor development and prolonged survival. These effects were also
associated with an increase in TP53, marked decrease in proliferation marker Ki67, and increase in TUNEL apoptosis marker immunostaining in PF-502–treated 2CKO tumors. Clinical studies will be needed to determine how individual and combined TP53 and TGF-β pathway alterations affect sensitivity to PI3K/mTOR inhibitors. In addition, inclusion of HPV+ HNSCC, which also shows concurrent PIK3CA activation and TP53 inactivation (36, 37), and sensitivity to mTOR inhibitor rapamycin in preclinical models (39), is warranted.

Other inhibitors of the PI3K/Akt/mTOR pathway have shown varying levels of activity in HNSCC and lung SCC models associated with status of PI3K, PTEN, TP53, or p73/YAP1. In a recent study, lung SCC lines harboring receptor tyrosine kinase activation, PI3K mutation, or amplification, and PTEN loss were reported to be most sensitive to a PI3K inhibitor, GDC-0941. Furthermore, activity of this inhibitor was enhanced by combination with chemotherapy (40). PI3K inhibitor BKM120 and PI3K/mTOR inhibitor BEZ235 showed activity in lung SCC with wtTP3 (41). In contrast, BKM120 and BEZ235 showed more limited cytotoxicity alone in HNSCC line SCC25 (42), which we noted was previously reported to lack TP53 resulting from deletion of 2 base pairs in codon 209 (43). BKM120 also lacked antiproliferative effect in cell lines without high PI3K p85-subunit expression (44). The dual PI3K/mTOR inhibitor, BEZ235, was recently reported to show preclinical activity in an HNSCC xenograft model with reduction in tumor volume (44). An Akt inhibitor was shown to reduce metastasis in an orthotopic model of wtTP3 HNSCC line SCC1 (22). We previously showed that an Akt inhibitor can enhance YAP in wtTP53 lines, an important cofactor for p73-mediated tumor suppression (18). However, the suppression of tumorigenesis but lack of complete regression observed with PI3K/Akt/mTOR inhibition by monotherapy with PF-502 or these agents suggests that combination with other therapies merits investigation.

As PF-502 induced TP53 and/or p73, and showed evidence of increased activity with radiation, combination of PI3K/mTOR inhibition with DNA-damaging therapies such as radiation or cisplatin active in HNSCC holds promise. Reduction of radiation toxicity by mTOR inhibitor rapamycin has been reported (45). Combination of PI3K/Akt/mTOR inhibition with other targeted agents could also potentially lead to improved antitumor effects with lower doses of each specific inhibitor, thereby limiting toxicity while improving efficacy (2). As we showed that MEK–ERK signaling is often coactivated with PI3K in HNSCC (5, 6), combined inhibition of these pathways could help improve on the tumorstatic effects observed with PI3K/mTOR inhibition alone.

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

Authors’ Contributions
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