Vemurafenib cooperates with HPV to promote initiation of cutaneous tumors

Matthew Holderfield\textsuperscript{1}, Edward Lorenzana\textsuperscript{1}, Ben Weisburd\textsuperscript{1}, Lisa Lomovasky\textsuperscript{1}, Lise Boussemart\textsuperscript{2}, Ludovic Lacroix\textsuperscript{3,4}, Gorana Tomasic\textsuperscript{3,4,6}, Michel Favre\textsuperscript{5}, Stephan Vagner\textsuperscript{6}, Caroline Robert\textsuperscript{2}, Majid Ghoddusi\textsuperscript{1}, Dylan Daniel\textsuperscript{1}, Nancy Pryer\textsuperscript{1}, Frank McCormick\textsuperscript{7} & Darrin Stuart\textsuperscript{1}

\textsuperscript{1} Novartis Institutes for Biomedical Research, Emeryville, CA
\textsuperscript{2} Dermatology Unit and INSERM U 981, Institut Gustave Roussy, Villejuif Paris-Sud, France
\textsuperscript{3} Department of Medical Biology and Pathology, Institut Gustave Roussy, Villejuif Paris-Sud, France
\textsuperscript{4} Translational Research Laboratory and Biobank, Institut Gustave Roussy, Villejuif Paris-Sud, France
\textsuperscript{5} Unité de Génétique, Papillomavirus et Cancer Humain, Institut Pasteur, Paris, France
\textsuperscript{6} INSERM U 981, Institut Gustave Roussy, Villejuif Paris-Sud, France
\textsuperscript{7} UCSF Helen Diller Family Comprehensive Cancer Center, San Francisco, CA

Potential conflict of interest

Several of the authors are or were employees of Novartis Institutes for Biomedical Research.
Abstract

Treatment with RAF inhibitors such as vemurafenib cause the development of cutaneous squamous cell carcinomas (cSCC) or keratoacanthomas (KA) as a side-effect in 18-30% of patients. It is known that RAF inhibitors activate the MAPK pathway and stimulate growth of RAS mutated cells, possibly accounting for up to 60% of cSCC or KA lesions with RAS mutations, but other contributing events are obscure. To identify such events, we evaluated tumors from patients treated with vemurafenib for the presence of HPV DNA and identified 13% to be positive. Using a transgenic murine model of HPV-driven cSCC (K14-HPV16 mice), we conducted a functional test to determine whether administration of RAF inhibitors could promote cSCC in HPV-infected tissues. Vemurafenib treatment elevated MAPK markers and increased cSCC incidence from 22% to 70% in this model. Furthermore, 55% of the cSCCs arising in vemurafenib-treated mice exhibited a wild-type Ras genotype, consistent with the frequency observed in human patients. Our results argue that HPV cooperates with vemurafenib to promote tumorigenesis, in either the presence or absence of RAS mutations.
Introduction

Nearly 50% of melanomas harbor a single activating Valine to Glutamic acid point mutation of the BRAF kinase (1). Constitutive BRAF activation leads to phosphorylation of the downstream effectors MEK, then ERK, which in turn activates transcription factors that promote proliferation of cancer cells. Phase II and phase III clinical trial results in BRAF\textsuperscript{V600E} mutated melanoma patients treated with the RAF inhibitor, vemurafenib, demonstrated improved survival and dramatic reduction in tumor burden (2, 3). Among the most common side effects is the emergence of non-melanocytic cutaneous tumors, including squamous cell carcinomas (cSCC), keratoacanthomas (KA), and verrucous papillomas (2-5). Pre-clinical data demonstrates that RAF inhibitors paradoxically stimulate ERK phosphorylation in RAS mutated cancer cells (6-9) through allosteric and catalytic mechanisms that relieve the auto-inhibition of wild-type RAF kinase (10). It is therefore hypothesized that paradoxical activation of the MAPK pathway induces cSCC and KA tumorigenesis in patients treated with RAF inhibitors.

Several groups have described the genetics of KA and cSCC induced by RAF inhibitors. Most notably 18-60% of the clinical biopsies harbor a \textit{RAS} mutation (11-13), and treatment with a vemurafenib analogue (PLX-4720) also decreased tumor latency in a mouse model for \textit{Hras} driven cSCC (13). However, 40-82% of KAs and cSCCs from RAF inhibitor treated patients are \textit{RAS} wild-type, suggesting that accelerated oncogenesis of \textit{RAS} mutated cells is not the only mechanism involved. Among the other mutated genes identified in cutaneous lesions from RAF inhibitor treated patients are \textit{FGFR3, TGFBR1, MYC, PIK3CA, TP53, CDKN2A, and VHL} (4, 11). While \textit{FGFR3} and \textit{TGFBR1} mutations may lead to \textit{RAS} activation and therefore hyperactivate the MAPK pathway in response to RAF inhibitors, it is unclear how critical \textit{RAS}-activating oncogenes are to vemurafenib-induced cSCC. Furthermore, the role of other drivers, such as infectious agents like HPV, have not been carefully examined. Therefore, we
used a transgenic mouse model that expresses the HPV16 early genes from the keratin 14 promoter (K14-HPV16) to evaluate the relationship between vemurafenib-treatment and HPV in driving cSCC (14).

**Materials and Methods**

**HPV screening of clinical biopsies.** Cellular DNA was extracted from biopsies of cutaneous lesions or normal skin. HPV types were identified using consensus FAP59/64 primers as described (15). Samples were also analyzed by a nested PCR method with two sets of degenerate primers (CP65/CP70 and CP66/CP69) located in the L1 open reading frame as described (16). Amplimers were sequenced and the HPV genotype was identified by comparison of sample sequence with Genebank database.

**RAS genotyping of clinical biopsies.** Genomic DNA was extracted from 10 to 20-μm-thick paraffin-embedded unstained slides of each skin lesion and full coding sequences of HRAS (NM_005343.2) exons 2 & 3, KRAS (NM_033360.2) and exons 2 & 3, NRAS (NM_002524.3). Sequences were analyzed by Sanger direct sequencing performed after PCR amplification of target exons. Sequencing reactions were carried out using the BigDye® Terminator Cycle Sequencing Kit software according to the manufacturer’s recommendations (Applied Biosystems, Forster City, CA). Sequencing reactions were analyzed on a 48-capillary 3730 DNA Analyzer®. Sequence reading and alignment were performed with SeqScape® software (Applied Biosystems).

**Tissue culture.** Proliferation of A375, SW620 (from ATCC), and GTL-16 cells (from S. Giordano, Cancer Research and Treatment, Turin, Italy) was measured by Cell Titer-Glo (Promega) and Rat-1 cells (from J. Gorski, University of Wisconsin) were grown in soft agar suspension. pERK quantification by sandwich immunoassay (MSD). All cell lines were routinely inspected for morphological changes and tested mycoplasma negative. A375, SW620 and GTL-16 were also inspected for DNA copy number and gene expression changes as previously described (17). Primary antibodies used for immunoblots: MEK, ERK, pMEK, pERK (Cell Signaling, 9122, 9102, 9121, and 9101 respectively).
**Mice.** FVB.Cg-Tg(KRT-14-HPV16) mice were obtained from Jackson Laboratories. Unless otherwise stated, mice 6 months old that had not yet developed cSCC received 15, 30 or 60 mg/kg once daily for 60 days of vemurafenib by oral gavage. For inhibitor combination studies, mice were given 3 mg/kg PD0325901 administered twice daily in addition to 60 mg/kg vemurafenib daily. Because cSCC most frequently occur on the ears or chest in this model, these tissues were collected from every mouse (in addition to any tumor present, regardless of location) and frozen in liquid nitrogen for PCR analysis or formalin fixed and paraffin embedded for histology. Non-transgenic littermates were used as negative controls. DUSP6 mRNA expression levels were quantified by QPCR from RNA in the collected tissues (Qiagen fibrous tissue RNA collection kit, Ambion cDNA synthesis kit). DUSP6 mRNA was normalized to 18s rRNA (Applied Biosystems: Mm00518185_m1 and 4319413E).

**Mouse histology.** Tissues were formalin fixed and paraffin embedded. Sections were stained with H&E or anti-pERK antibody (Cell Signaling 9121). Slides were randomized and blinded before histology scores determined by a pathologist. Skin and tumor samples were ranked as normal, premalignant or malignant cSCC (Figure 4C-F). Premalignant histology included moderate to severe hyperplasia, dysplasia and hyperkeratosis. K14-HPV16 cSCCs are marked by keratin “pearls” of invasive well differentiated squamous carcinoma (WDSC) occurring primarily on the ventral surface of the ear, or by a keratin cap containing heterogeneous regions of moderate to poorly differentiated squamous carcinoma (M/PDSC) occurring primarily on the chest and trunk. Malignant phenotypes included any M/PDSC, WDSC and KA-like lesions.

**Ras genotyping of mouse K14-HPV16 cSCC.** Genomic DNA was collected from 9 cSCCs and 1 non-tumor skin sample from untreated K14-HPV16 mice, and 9 cSCCs and 1 non-tumor skin sample from K14-HPV16 mice treated with 60 mg/kg vemurafenib. 100bp x 2 paired end sequencing (Illumina) was performed after mouse exome capture (Agilent). Sequences were aligned to the MM9 genome using
bwa v0.6.1 (18) and processed according to GATK v2 (19) best practices by running the IndelRealigner, MarkDuplicates, and TableRecalibration tools per sample, and using dbSNP (20) for known variants. The GATK UnifiedGenotyper (18) was then used to call variants on all 20 samples together with non-default options -dcov 1000 and -rf MappingQualityZero. Called SNPs and INDELs were hard-filtered with the GATK VariantFiltration tool using criteria FS > 80.0, HRun > 5, QD < 2.0, MQ < 30.0.

**Results**

**Vemurafenib paradoxically activates the MAPK pathway in RAF wild-type epidermis.** To determine if clinically relevant exposures to vemurafenib are sufficient to activate the MAPK pathway and promote cSCC tumorigenesis in vivo, non-transgenic FVB/N mice were treated with 60 mg/kg vemurafenib (equivalent to the Phase III dose (2)) for 60 days. Although none of the mice treated developed spontaneous tumors, subtle evidence of elevated MAPK activity was observed in epithelial tissues. A modest increase in nuclear phosphorylated ERK staining was observed in non-glandular gastric epithelium (Supplementary Figure S2) and epidermis (Figure 1A). Because transcriptional targets of the MAPK pathway are often a more sensitive marker for ERK activity (21), DUSP6 mRNA levels were measured by QPCR and were found to be increased 3-fold in skin from vemurafenib treated mice (Figure 1B), demonstrating that vemurafenib paradoxically activates the MAPK pathway in genetically wild-type mouse epidermis, but is insufficient for cSCC tumorigenesis.

**Vemurafenib paradoxically activates the MAPK pathway in RAF/RAS wild-type cells.** Having observed elevated MAPK markers in vemurafenib treated mice, we wished to test if a RAS oncogene is required for vemurafenib to promote tumorigenesis. To test this in vitro, three cancer cell lines with different RAS/RAF mutations were treated with vemurafenib. While vemurafenib effectively inhibited ERK phosphorylation and proliferation of BRAF mutated cells, ERK phosphorylation was stimulated and proliferation increased in RAS/RAF wild-type cells, though to markedly higher levels in the KRAS mutated
cell (Figure 1C). High doses of vemurafenib similarly increased ERK phosphorylation and induced anchorage independent growth of RAS/RAF wild-type Rat-1 fibroblasts (Figure 1D), demonstrating that vemurafenib treatment is sufficient to activate the MAPK pathway and promote a transformation phenotype. However, the magnitude of activation may be dependent upon the underlying genetics, and vemurafenib induced activation appears to be particularly exaggerated in RAS mutated cells.

**A subset of cutaneous lesions from vemurafenib treated patients are HPV positive and RAS wild-type**

Given these observations, we hypothesized that paradoxical activation of the MAPK pathway by RAF inhibitor treatment may promote cSCC tumorigenesis only in the presence of pre-existing genetic lesions. Several common tumor suppressor mutations have been identified in cSCCs from patients treated with RAF inhibitors including TP53, CDKN2A, and VHL (4, 11). In addition to host mutations, the contribution of viral oncogenes has also been implicated in cSCC tumorigenesis. The majority of non-melanocytic lesions occurring in vemurafenib-treated patients include several benign skin lesions with strong associations with HPV, including venereal warts and verrucous papillomas (5), which strongly implicates a role for HPV. Although the frequency is low, expression of HPV capsid protein has been observed in one cSCC from a patient treated with the RAF inhibitor dabrafenib (22), and HPV DNA was observed in a separate case study (23).

To determine if an HPV infection may contribute to cutaneous tumor initiation in patients treated with vemurafenib, 62 benign or malignant cutaneous lesions from 44 patients were collected and tested for presence of HPV DNA. Eight of the lesions (13%) tested positive for one of 6 HPV types (Figure 2), indicating that HPV may contribute in a subset of cases. Because HPV can also be found on normal skin and may be considered commensal with human tissue, we tested several tumors from the same patients including normal skin samples when possible. In four cases, patients with HPV-positive tumors also had additional skin tumors or normal skin samples that were HPV negative. In one patient, two
different HPV types (HPV9 and 49) were found in two distinct skin tumors whereas three additional tumors from the same patient were negative for HPV DNA. Additional indirect evidence of a viral contribution was observed in several HPV negative tumors. Koilocyte-like cells were observed in papillated epidermal hyperplasia with a thickening of the granular layer, as commonly seen in viral warts (Supplementary Figure S1).

Because RAS mutations frequently occur in vemurafenib induced patient tumors, each tumor was also genotyped for HRAS, KRAS and NRAS mutations. As shown in Figure 2A, 10 (16%) RAS mutations (5 HRAS, and 5 KRAS mutations) were identified, which is approximately equivalent to the frequency of HPV positive tissues. While HPV DNA did not appear to associate with any histological category, HRAS mutations were only observed in KAs and KRAS mutations were exclusive to verrucous papillomas. Interestingly, co-occurrence of a RAS mutation and HPV was only observed for one HRAS mutated KA (Figure 2B), suggesting that if HPV infection contributes to tumor initiation in vemurafenib treated patients, it primarily occurs independent of RAS mutations.

**Vemurafenib promotes Ras wild-type tumorigenesis in K14-HPV16 mice.** To test if vemurafenib can promote cSCC tumorigenesis in HPV infected keratinocytes, we used a transgenic mouse model that expresses the HPV16 early genes from the keratin 14 promoter (K14-HPV16) (14). These mice exhibit epidermal hyperplasia, hyperkeratosis and many develop cSCCs and KA-like tumors. To our knowledge, no mutations have been described in spontaneous K14-HPV16 cSCCs. Tumor-free mice between 5 and 7 months old were treated daily with vemurafenib and tumor volume was monitored for 60 days. Activation of the MAPK pathway in epidermis was both time and dose dependent. Low doses (15 and 30 mg/kg) of vemurafenib moderately increased dermal DUSP6 expression only at early time points, while 60 mg/kg showed sustained increase in DUSP6 expression at 12 and even 24 hours post treatment (Figure 3A). Neither the 15 nor 30 mg/kg cohort significantly changed the frequency of cSCC and/or pre-
malignant phenotypes. However, the frequency of cSCC was significantly increased from 22% in vehicle treated mice to 70% in the 60 mg/kg vemurafenib cohort (Figure 3B-C).

To test for the presence of Ras oncogenes, cSCCs were collected from both vemurafenib treated and untreated K14-HPV16 mice and genomic exons were sequenced. Somewhat surprisingly, 100% (9/9) of vemurafenib naïve tumors sequenced carried an activating Ras mutation, 8 of which were Kras mutated, and 1 Hras (Q61L) mutated (Figure 3D), suggesting that a Ras oncogene is required for cSCC in this model. However, only 44% (4/9) of the cSCCs from vemurafenib treated mice were Ras mutated (Figure 3D), suggesting that the increase in cSCC frequency is due to an increase of Ras wild-type tumors.

Tumors from both vehicle and vemurafenib treated mice were also stained for ERK phosphorylation, and areas of every tumor stained positive (Supplementary Figure S3), suggesting that K14-HPV16 cSCC requires ERK activation. However, no other Ras activating mutations, and no other known oncogenes were observed in the vemurafenib treated, Ras wild-type tumors. Nor did any set of mutations distinguish Ras wild-type cSCC from Ras mutated or vehicle treated cSCC.

**K14-HPV16 cSCC is MEK dependent.** These sequencing data suggest that the requirement for a Ras mutation in K14-HPV16 cSCC is bypassed by vemurafenib treatment. Conceivably, cSCC in this model requires MAPK pathway activation, which occurs frequently through a Ras mutation, but can also occur through paradoxical activation of ERK signaling in vemurafenib treated mice. If correct, then blockade of the MAPK pathway downstream of RAF should prevent the increased incidence of cSCC caused by vemurafenib. Consistent with this hypothesis, co-treatment of a RAF and MEK inhibitor in clinical trials reduced the frequency of squamous cancers compared to RAF inhibitor treatment alone (24). To test if this is also true for K14-HPV16 cSCC, mice were treated with a combination of vemurafenib and a MEK inhibitor, PD0325901. DUSP6 mRNA expression was elevated in vemurafenib treated skin, and reduced to background levels by PD0325901 (Figure 4A), showing that 3 mg/kg PD0325901 is sufficient to
prevent any paradoxical MAPK activation caused by vemurafenib. Mice treated with PD0325901 also had reduced hyperkeratosis and improved grooming (Supplementary Figure S4). Concomitant treatment of 60 mg/kg vemurafenib and 3mg/kg PD0325901 also significantly reduced the frequency of cSCC from 70% in vemurafenib treated mice to 17% in vemurafenib + PD0325901 treated mice (Figure 4B). However, none of the mice treated with PD0325901 as a single agent developed cSCCs during the study, suggesting that MEK inhibition prevents cSCC tumor initiation in K14-HPV16 mice.

To test if MEK activity is required for tumor maintenance, mice with established spontaneous cSCC were treated with PD0325901 for 2 weeks and tumor volume was monitored. There were 5/8 partial responses and 2 complete responses in the 3 mg/kg cohort, and all of the mice treated with 10 mg/kg PD0325901 showed a complete response after 2 weeks (Figure 5A-B, and Supplementary Figure S4). Both cohorts had reduced pERK staining within the tumor, though pERK partially returned after 5 hours in tumors treated with 3 mg/kg, yet remained suppressed in tumors treated with 10 mg/kg (Figure 5C), suggesting the higher response rate is due to sustained MEK inhibition. Together, these results strongly indicate that MEK activity is required for cSCC tumor maintenance.

Discussion

While it is known that RAF inhibitors accelerate RAS mutant tumor growth, it is unclear why roughly 40-80% of cSCCs from patients treated with vemurafenib are RAS wild-type (11, 13). In the present study vemurafenib not only increased the incidence and accelerated tumorigenesis, but also clearly induced Ras wild-type cSCC in K14-HPV16 mice (Figure 3C-D). This suggests that vemurafenib is required for initiation of cSCC in Ras wild-type cells, and may then explain the emergence of Ras wild-type cSCC in RAF inhibitor treated patients. Also consistent with the clinical observations (25), co-treatment with the MEK inhibitor PD0325901 prevented vemurafenib induced cSCC (Figure 4B). Moreover, treatment of established cSCC with PD0325901 caused tumor regression (Figure 5), demonstrating that MAPK activity
is not only required for initiation, but also for cSCC maintenance. However, it is important to note that vemurafenib induced cSCC was only observed in K14-HPV16 transgenic mice, and not in HPV negative, non-transgenic littermates. Therefore, treatment with vemurafenib alone, while sufficient to paradoxically activate the MAPK pathway in mouse dermis, and necessary for Ras wild-type tumorigenesis in K14-HPV16 mice, was not sufficient to initiate cSCC. Clearly loss of tumor suppressor function is a minimum requirement for vemurafenib-induced cSCC.

HPV has been linked to cancer progression for decades due to the transformation potential of HPV oncogenes. HPV has been observed in both mucosal and cutaneous tumors, though the mechanism of oncogenesis likely differs. Cervical and head & neck cancers are clearly linked to alpha-HPV genotypes, which exhibit mucosal tropism, while beta-HPVs are more frequently associated with cutaneous disease. Although the mechanism of transformation for beta-HPV is not fully understood, transgenic mouse studies demonstrate that keratinocyte specific expression of either the HPV8 (beta-HPV) or HPV16 (alpha-HPV) genes can promote cSCC in the FVB/N background (14, 26). Additionally, while expression of HPV transcripts can be seen in established cervical cancers, expression of HPV genes is often undetectable even in cSCC from HPV positive patients (27), indicating that HPV does not play an active role in cSCC tumor maintenance. Data presented here demonstrate that a subsequent Ras mutation is also required for HPV16 driven tumorigenesis in the K14-HPV16 model (Figure 3D). These data are consistent with the function of HPV16 E6 and E7 oncogenes, which target P53 and pRB tumor suppressors to prevent the DNA damage response, and implicate HPV in cSCC initiation rather than tumor maintenance. Although it is unclear if beta-HPV initiate transformation through a similar mechanism, 27% (6/22) of cSCC from K14-HPV8 transgenic mice develop a spontaneous Hras mutation (28), compared to 11% (1/9) in the HPV16 model (Figure 3D). Further investigation in beta-HPV models may therefore reveal common mechanisms of oncogenesis.
These data therefore elucidate a synergy between premalignant, HPV infected tissues and paradoxical MAPK activation in patients treated with RAF inhibitors. HPV oncoproteins likely promote tumor initiation by increasing the frequency of premalignant mutations, while paradoxical activation of the MAPK pathway promotes both initiation and maintenance in patients treated with RAF inhibitors. Because most of the human population tests positive for cutaneous HPV (29), the majority of patients treated with RAF inhibitors are likely susceptible. Although only 18-30% of patients treated develop cSCC and/or KA (2, 3), these figures may under-represent the frequency of RAF inhibitor-induced tumorigenesis. In a separate study of 42 patients, 100% presented with at least one adverse skin reaction, and the most common events were verrucous papillomas (79%) (5). Patients who develop cutaneous tumors frequently acquire multiple primary lesions, which can affect entire limbs or chest (30, 31), a phenotype consistent with an infectious disease. Furthermore, the pathology of tumors is also not limited to cSCC and KA. Cases of pilaris-like eruptions, acantholytic dyskeratosis, verrucous keratosis, cystic lesions, papules, verrucous papillomas and basal cell carcinomas have been documented (30-34) but were not reported as adverse events in the clinical trials (2, 3). The diversity of cutaneous lesions observed in patients treated with RAF inhibitors may also reflect the presence of multiple oncoviruses, including Merkel cell polyomavirus (23), or multiple unrecognized HPV genotypes that each requires MAPK activation for tumorigenesis. Disruption of ERK activation in these tissues by combining MEK and RAF inhibitors therefore appears to be an effective strategy to treat BRAFV600E mutant melanomas, and to prevent spontaneous cutaneous tumors concurrently.

References


Figure Legends

**Figure 1.** Vemurafenib activates the MAPK pathway in RAF wild-type tissues in vivo and RAF wild-type cells in vitro. **A,** FVB/N mice were treated with vehicle control or 60 mg/kg vemurafenib for 60 days. Skin from the ventral trunk was collected 10 hours after the last drug administration. Formalin fixed/paraffin embedded sections were stained for phospho-ERK. **B,** RNA was also collected from frozen skin and DUSP6 mRNA was quantified by QPCR (p=0.004, Student’s T-test). **C,** A375 (*BRAF*V600E), SW620 (*KRAS*G12V), and GTL-16 (*BRAF*WT/*RAS*WT) cells treated with the indicated doses of vemurafenib, pERK levels were measured 4 hours after treatment and proliferation measured after 5 days. Data expressed as % of DMSO treated cells. **D,** RAT-1 fibroblasts were treated with the indicated doses of vemurafenib for 1 hour. pMEK, MEK, pERK and ERK protein levels shown by immunoblot. RAT-1 fibroblasts were grown in soft agar suspension and treated with vemurafenib and bright field images were taken after 7 days of growth.

**Figure 2.** Frequency of *RAS* mutation and HPV status in vemurafenib induced cutaneous tumors. **A,** Cutaneous lesions from patients treated with vemurafenib. Frequency of HPV and *RAS* mutations by histological type. **B,** Co-occurrence of *HRAS* or *KRAS* mutation and HPV type for each tumor sample.

**Figure 3.** Vemurafenib increases incidence of *RAS* wild-type cSCC. **A,** Time-course of DUSP6 mRNA levels from ear and ventral trunk skin from K14-HPV16 mice treated with the indicated dose of vemurafenib, expressed as % of a vehicle treated control. Each data point represents a single animal. Range of DUSP6 expression for 5 vehicle treated mice shaded in gray. **B,** Representative samples of the histological scoring used. Normal (top left panel) skin from K14-HPV16 mice is slightly hyperplastic, moderate to severe hyperplasia (lower left panel) and dysplastic (top right panel) tissues were classified as “premalignant” and invasive carcinomas (lower right panel) were classified as cSCC. **C,** Frequency of histological scoring for each treatment cohort (n=18, 14, 13, and 23 for cohorts 0, 15, 30 and 60 mg/kg.
vemurafenib respectively; 60 day endpoint; * p=0.006, Fisher’s Exact Test). D, RAS mutation status for cSCC tumor samples from mice treated with vehicle control or 60 mg/kg vemurafenib. No NRAS mutations were observed.

**Figure 4. Co-treatment with PD0325901 prevents vemurafenib induced cSCC.** Mice were treated with 60 mg/kg vemurafenib QD (Vem.), 3 mg/kg PD0325901 BID (PD.), 60mg/kg Vem. QD + 3mg/kg PD. BID or vehicle control. A, Skin from mice was collected 10 hours post treatment and DUSP6 mRNA levels were measured by QPCR (*p=0.006, **p=0.002, ***p=0.002, n=4, Student’s T-test) B, Frequency of histological scoring (n=18, 23, 12, and 11 for Vehicle, Vem., PD., and Vem. + PD. cohorts respectively; †p=0.007, ††p=0.006, †††p=0.0006, Chi-square).

**Figure 5. K14-HPV16 cSCCs are MEK dependent.** Mice harboring spontaneous cSCC were treated with PD0325901 BID for 2 weeks. Tumor volume was measured at start and end of study. A, Waterfall plot of tumor response to PD0325901, data expressed as % change of tumor volume after 2 weeks of treatment (horizontal line shows PR ≥ 30%, CR = 100%). B, Representative images of tumor responses before and after 2 weeks of treatment with 10 mg/kg PD0325901. C, Representative images for pERK staining of cSCCs 5 hours after treatment with vehicle 3 mg/kg PD0325901, or 10 mg/kg PD0325901 (n=3 for each condition).
### Figure 2

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Figure 3

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Figure 4

(A) Bar chart showing the expression levels of DUSP3 in different treatment groups. Significant differences are indicated by asterisks: * (p < 0.05), ** (p < 0.01), *** (p < 0.001).

(B) Bar chart depicting the percentage of mice with different histological classifications. Significant differences are indicated by Roman numerals: † (p < 0.05), ‡ (p < 0.01), ††† (p < 0.001).

Histology:
- Oral squamous cell carcinoma (oSCC)
- Pre-malignant
- Normal

Groups:
- Vehicle
- Vemurafenib
- Vemurafenib + PD0325901
- PD0325901
Figure 5

A

B

Day 0

Day 14
Vemurafenib cooperates with HPV to promote initiation of cutaneous tumors

Matthew Holderfield, Edward Lorenzana, Ben Weisburd, et al.

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