BRAF inhibitor resistance mechanisms in metastatic melanoma; spectrum and clinical impact

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Abstract

Purpose: Multiple BRAF inhibitor resistance mechanisms have been described, however their relative frequency, clinical correlates, and effect on subsequent therapy have not been assessed in patients with metastatic melanoma.

Experimental Design: Fifty-nine $BRAF^{V600}$ mutant melanoma metastases from patients treated with dabrafenib or vemurafenib were analyzed. The genetic profile of resistance mechanisms and tumor signaling pathway activity was correlated with clinicopathologic features and therapeutic outcomes.

Results: Resistance mechanisms were identified in 58% progressing tumors and BRAF alterations were common. Gene expression analysis revealed that MAPK activity remained inhibited in 21% of resistant tumors, and the outcomes of patients with these tumors were poor. Resistance mechanisms also occurred in pre-treatment biopsies and heterogeneity of resistance mechanisms occurred within patients and within tumors. There were no responses to subsequent targeted therapy, even when a progressing tumor had a resistance mechanism predicted to be responsive.

Conclusions: Selecting sequential drugs based on the molecular characteristics of a single progressing biopsy is unlikely to provide improved responses, and first-line therapies targeting multiple pathways will be required.

Translational Relevance: Heterogeneity of BRAF inhibitor resistance mechanisms is common between patients, within patients and within individual tumors. Re-activation of MAPK signaling in resistant tumors is common and prognostic, and resistant tumor cells can exist prior to therapy. These results suggest that adaptive clinical trials in metastatic melanoma, which involve the selection of sequential targeted drugs based on the molecular profiling of a single progressing biopsy, are unlikely to provide durable responses. Anticipating the emergence of multiple resistance mechanisms by initiating drug treatments targeting multiple pathways may have more success than an adaptive sequential approach.
Introduction

The serine/threonine kinase BRAF is constitutively activated via mutations in 40-60% of cutaneous melanomas. The valine substitution at residue 600 accounts for over 90% of BRAF mutations and causes the RAS-independent activation of the mitogen activated protein kinase (MAPK) cascade (1, 2). Potent inhibitors of BRAF\textsubscript{V600} mutant protein, dabrafenib and vemurafenib, have produced response rates of 50-60%, and prolong the progression-free (PFS) and overall survival (OS) of BRAF\textsubscript{V600E} melanoma patients, compared with dacarbazine (3, 4). Dabrafenib also causes regression of brain metastases in BRAF\textsubscript{V600E/K} melanoma patients (5).

Despite this activity, 50% of patients treated with dabrafenib or vemurafenib develop disease progression 6 to 7 months after starting treatment (6, 7). Multiple mechanisms of acquired resistance have been described including elevated expression of the kinases CRAF, COT1 or mutant BRAF (8-11), activating mutations in \textit{N-RAS}, \textit{MEK1} or \textit{AKT1} (12-14), aberrant splicing of \textit{BRAF} (15), activation of phosphatidylinositol-3-OH kinase (PI3K) via the loss of PTEN (16) and persistent activation of receptor tyrosine kinases, including PDGFR\textsubscript{B}, IGF-1R and EGFR (12, 17, 18). Interactions between melanoma tumors and their microenvironment can also elicit innate resistance to BRAF inhibitors and stromal-derived hepatocyte growth factor has been shown to activate the receptor tyrosine kinase MET along with MAPK and PI3K signaling in melanoma cells (19, 20).

The relative frequency of these resistance mechanisms and correlation with clinical outcome to BRAF inhibitor therapy is poorly understood. No single study has analyzed all known mechanisms of resistance in a single patient cohort nor correlated them with clinicopathologic features or outcomes. Previous studies indicate that approximately 32% of patients progressing on vemurafenib therapy have melanomas expressing BRAF splice variants (15), 23% have melanomas with activating \textit{N-RAS} mutations (10, 15, 21), and a further 31% have melanoma metastases with \textit{BRAF}
copy number gains (10). The robustness of these proportions in resistance to dabrafenib, the extent of resistant heterogeneity within patients and the clinical correlates of each resistance mechanism remain to be established. We analyzed 59 tumors; 38 progressing (Prog) and 21 matched pre-treatment melanoma tumors from 30 BRAF<sup>V600</sup> mutant melanoma patients receiving dabrafenib or vemurafenib. The genetic profile of resistance mechanisms and tumor signaling pathway activity was correlated with clinicopathologic features and therapeutic outcomes.

Methods

Patients and BRAF inhibitor therapy

Patients included in this study had BRAF<sup>V600</sup> mutant metastatic melanoma, had not received prior MAPK inhibitors or immunotherapy, and were treated with either dabrafenib (150mg twice daily or total daily dose of at least 300mg daily) or vemurafenib (960mg twice daily) as part of a clinical trial (3-5, 22, 23) (including NCT01378975) or an access program. All patients had a progressing melanoma metastasis (Prog) resected that was classified as either: a) a newly identified metastasis that arose during treatment, b) a pre-existing metastasis, that initially responded and subsequently progressed on BRAF inhibitor therapy, or c) a pre-existing metastasis that never responded. Where available, a matched pre-treatment melanoma tissue sample obtained prior to commencing BRAF inhibitor was included in the analysis.

Clinical outcome was assessed using best objective response, progression-free survival (PFS) and overall survival (OS) from commencement of BRAF inhibitor. The best objective response and PFS was determined using RECIST (24) for patients on clinical trials. For patients not on a clinical trial or those without measurable disease at treatment commencement, the treating physician determined disease progression and categorized the best objective response as ‘response’ (≥30% reduction in tumor burden) or ‘no response’ (<30% reduction). Informed consent was obtained for each patient under approved Human Research Ethics Committee protocols.
Melanoma Tissue Samples

Fresh melanoma samples were macrodissected by a pathologist and enriched tumor portions snap-frozen. Frozen tumor sections were cut, stained with hematoxylin and eosin and scored for the following parameters: % non-tumor cells, % necrosis, degree of pigmentation, predominant cell shape, and cell size of the most cellular portion of tumor (25). Tumor foci were carefully macrodissected utilizing the marked frozen section as a guide to meet minimum criteria for tumor cell content (>80%) and amount of necrosis (<30%). High-percentage tumor content was verified by examining post-macrodissection frozen section slides. Total tumor RNA and DNA was extracted as described previously (25). A short-term Prog-derived cell culture was used to analyze resistance mechanisms in one patient (patient 27).

Resistance screen

An RT-PCR resistance screen was used to examine the expression of BRAF splice variants, the complete coding sequence of MEK1, MEK2 and N-RAS cDNAs and the 5’ half of the AKT1 cDNA. This region of AKT1 encompassed amino acids 1-200 which includes the common activating E17K (COSMIC; 84% of tumor-associated AKT1 mutations) and the BRAF inhibitor resistance allele Q79K (14). BRAF relative copy number was determined by quantitative PCR using the Corbett Rotorgene 6000 as previously described (11). The allele frequencies of the wild type and V600E mutant BRAF were also assessed using allele specific PCR in Prog tumors showing BRAF copy number gains. The allele specific primers (26) showed similar PCR efficiencies (i.e serial dilution standard curves had equivalent slopes; data not shown) and relative BRAF V600:E600 allele frequencies were calculated from the change in cycle threshold (Ct).

Reverse transcription reactions were performed using the Superscript III First-Strand Synthesis kit (Invitrogen) with the oligo dT primer. The MEK1, MEK2, N-RAS and AKT1 gene products were
each amplified from cDNA using Taq polymerase (Fisher Biotech, Wembley, WA, Australia) and BRAF cDNA was amplified with Pfx polymerase (Life Technologies, Carlsbad, CA). PCR products were purified using QIAquick PCR purification kit (Qiagen, Limburg, Netherlands) followed by Sanger sequencing on the 3730xl DNA Analyser (AGRF, Westmead, NSW, Australia). Amplification and sequencing primers are listed in Table S7. The identity of Prog mutations was confirmed using an independent RT-PCR product, and where available Prog-associated alterations were examined in matched pre-treatment melanoma samples.

**Gene Expression Analysis**

Gene expression analysis was performed on matched pre-treatment (n=21) and Prog (n=29) biopsies derived from 21 patients, using the Sentrix HumanHT12 v.4.0 Expression BeadChip (Illumina, San Diego, CA, USA). Two responding (i.e. shrinking) melanoma samples taken early during BRAF inhibitor therapy (EDT; 3-15 days after therapy initiation; patients 5 and 10) were also included in these gene expression analyses. Gene expression data was normalized using the cubic spline function. Rank ordering of gene expression data was carried out using the linear model for microarray module (LimmaGP) in GenePattern and analyses was performed using gene set enrichment analysis in pre-ranked mode (GSEA pre-ranked) (27, 28). Two established transcriptional signatures of MAPK activation (12, 29) were included and analyzed as part of the c6.all.v4.0 oncogenic gene set. A false discovery rate (FDR) q<0.1 was used for comparisons between Prog melanoma tumors and matched pre-treatment samples. Box-plots were used to illustrate the distribution of MAPK activation scores (mean log2-transformed expression of MAPK activation gene transcripts). Medians and interquartile ranges were applied to summarize the distributions, and the Mann-Whitney U test was used to determine the differences between the pre-treatment and Prog tumors.
The microarray platform and data have been submitted to the Gene Expression Omnibus public database at the National Center for Biotechnology Information, following the minimum information about microarray gene experiment guidelines. The accession number is GSE50509.

**Immunohistochemistry**

All IHC staining was performed on a Dako Autostainer Plus (Dako, Glostrup, Denmark), utilizing the EnVision™ FLEX, High pH visualization system (K8024, Dako, Glostrup, Denmark) according to the manufacturer’s protocol. Sections (4µm) were baked at 58°C for 60 mins, then underwent deparaffinization and antigen retrieval using the heat-induced epitope retrieval (HIER) method using Envision Flex Target Retrieval Solution (High pH) in a PT link unit (Dako, Glostrup, Denmark). Slides were incubated with the primary antibodies IGF-1R 1:200 (CS-3027, Cell Signaling Technology, Danvers, MA), PDGFRβ 1:50 (CS-3169, Cell Signaling Technology, Danvers, MA), and pAKT Ser473 1:75 (CS-3787, Cell Signaling Technology, Danvers, MA) for 45 mins at room temperature. Antibody detection was performed using the Dako Envision Flex HRP (Dako, Glostrup, Denmark) and visualized using 3,3’-diaminobenzidine (Dako, Glostrup, Denmark), and the slides were counterstained with Harris’s Hematoxylin.

H&E and immunostained slides were evaluated twice by two independent observers (AMM and RAS) blinded to clinical and resistance data. Expression in Prog tumors was determined relative to the matched pre-treatment sample, and between Prog samples, using a 4 tier semi-quantitative scale of staining intensity in tumor cells (0=no staining, 1=weakly positive staining, 2=moderately positive staining, 3=strongly positive staining). For IGF-1R and PDGFRβ, membranous staining was scored, and for pAKT both nuclear and cytoplasmic staining was scored.
Cell culture, constructs and lentivirus transductions

SKMel28 and A375 melanoma cells were obtained from Prof. P. Hersey (Kolling Institute, University of Sydney) and short-term cultures were established from a subset of patients as previously described (30). Cells were grown in Dulbecco’s Modified Eagle Medium (DMEM) with 10% FBS and glutamine (Gibco BRL) and cultured in a 37°C incubator with 5% CO₂. Stocks of dabrafenib (supplied by Active Biochem) were made in dimethyl sulfoxide (DMSO). Cell authentication was confirmed using the StemElite ID system from Promega. Lentiviruses were produced in HEK293T cells as described previously (31). Cells were infected using a multiplicity of infection of 1-5 to provide an efficiency of infection above 90%. Wild-type and mutant FLAG-tagged MEK1 and MYC-tagged MEK2 constructs were each cloned into the pCDH-CuO-MCS-EF1-CymR-PURO and pCDH-CuO-MCS-IRES-copGFP lentiviral vectors, respectively.

Western blotting

Total cellular proteins were extracted and analyzed as previously described (30). Western blots were probed with the following antibodies: total ERK (137F5; Cell Signaling, Danvers, MA), phosphorylated ERK (E-4; Santa Cruz, Santa Cruz, CA), MYC (A-14; Santa Cruz), FLAG (Sigma Aldrich, St. Louis, MO), MEK1/2 (L38C12, Cell Signaling), ATM (D2E2, Cell Signaling) and β-actin (AC-74; Sigma-Aldrich).

Clonogenic assays

Approximately 96h post transduction, melanoma cells were seeded at 25000/well onto 6-well culture plates and allowed to grow for 24 hours followed by the desired treatment. Cells were then washed twice with ice-cold PBS and fixed with ice-cold methanol for 1 minute. After aspirating methanol from plates, 0.1% crystal violet (Scienclab.com, Inc., TX) solution was added and the plate was incubated at room temperature for 5 minutes. Distilled water was used to rinse the plate. Colony-forming assays were performed at least twice in triplicate.
Statistical Methods

Univariate time to event analyses were conducted with the Kaplan-Meier method together with the Log Rank test for significant differences between groups. Multivariate times to event analyses were conducted with Cox regression and the forward stepwise variable selection method (inclusion criteria p<0.01). Clinical features were tested for association with categorical groupings of resistance mechanisms using the Fisher’s exact test and the Mann-Whitney U test as appropriate. Two-tailed p-values less than 0.05 were considered significant for all tests. Analyses of clinical statistics were carried out with the IBM SPSS Statistic 21.0 software package.

Results

Patients and Melanoma Tissue Samples

We analyzed 59 fresh-frozen melanoma tumor samples derived from 30 BRAFV600 mutant metastatic melanoma patients who received either dabrafenib (22/30; 73%) or vemurafenib (27%) (Table 1); 38 were Prog metastases and 21 were matched pre-treatment tumors. All patients were on BRAF inhibitor at the time of Prog biopsy except patients 27 and 29 who had ceased vemurafenib 10 and 18 days prior to resection, respectively. The median time to resection of the Prog lesion was 32.5 weeks (range 8.4-150.7). Prog tumors included 14 newly identified metastases, 17 pre-existing and initially responding tumors, two tumors that never responded to treatment and five subcutaneous Progs not categorized (Table 1). Twenty patients had $BRAF^{V600E}$ (67%), nine had $BRAF^{V600K}$ (30%) and one had $BRAF^{V600R}$ melanoma (3%). Nearly all (28/30, 93%) patients experienced tumor regression with treatment. The median PFS was 22.0 weeks (95% CI: 13.0-31.0) and the median OS was 80.7 weeks (95% CI: 46.0-115.4) (Table 1).

Resistance Profile

A resistance mechanism was identified in 22 of 38 (58%) Prog tumors (Table 1; Figure 1A); $BRAF$
splice variants were detected in 12 (32%), oncogenic *N-RAS* mutations in 3 (8%), *BRAF* amplification in 3 (8%), *MEK1/2* mutations in 3 (8%), an *AKTI* mutation in 1 (3%) and increased levels of IGF-1R in 1 (3%) Prog tumor(s). Twenty-nine Prog tumors underwent Gene Set Enrichment Analysis (GSEA) of gene expression; six (21%) showed loss of MAPK activity signatures, i.e. MAPK pathway signaling was inhibited in these progressing lesions compared to the matched pre-treatment melanoma, and 23 (79%) showed re-activation of MAPK signaling (Table 1, Figure 1B).

*BRAF* splice transcripts and *BRAF* amplification

Alternative *BRAF* splice transcripts were detected in 12 of 38 (32%) Prog tumors (Figure S1, S2). A single full-length *BRAF* RT-PCR product was present in matched pre-treatment samples from nine of these 12 patients. Full-length *BRAF* was usually heterozygous for wild-type and mutant transcripts, indicating correct BRAF splicing from both alleles in the pre-treatment sample (Figure S1). In contrast, the Prog-specific shorter *BRAF* transcripts were always homozygous for *BRAF*\(^{V600E}\) and lacked exons 2-10 (n=3 Prog), exons 2-8 (n=4 Prog) or exons 4-8 (n=4 Prog), with one tumor having two shorter transcripts (lacking exons 2-10 and 2-8) (Figures S1, S2). Immunoblot analyses of one Prog-derived short-term culture (Patient 9; Prog lacking exons 2-10) using the V600E-specific BRAF antibody (32) confirmed expression of the full-length BRAF\(^{V600E}\) protein and the expected 41 kDa BRAF mutant truncated variant (Figure S1). *BRAF* copy number gains were detected by qPCR in 3 of 38 Prog samples (8%; 2 to 4 fold copy number increase) (Table 1) and allele specific PCR confirmed that the mutant allele was amplified relative to the wild type *BRAF* DNA (Figure S3).

**Oncogenic Mutations in N-RAS, MEK1, MEK2 and AKTI**

Oncogenic mutations in *N-RAS* (G13R or Q61K) were identified in 3 of 38 (8%) Prog samples (Figure 1A). An *N-RAS*\(^{P18S}\) mutation was identified in the Prog and matched pre-treatment biopsies.
derived from patient 4. This missense mutation has been reported in the 1000 Genomes project (33), has a frequency of 0.01% in European American populations and was excluded as a resistance mechanism.

Five MEK1 (K57E, I111S, P124S, G176S, E203K) and one MEK2 (F57C) mutations were identified in seven Prog tumors (Figure S2, S4). The I111S, P124S and G176S MEK1 mutants and the F57C MEK2 mutant occurred in the pre-treatment tumors; I111S and P124S have been shown not to preclude clinical response (34). Functional analyses confirmed that MEK1\textsuperscript{K57E} and MEK2\textsuperscript{F57C} mutants restored ERK activation in the presence of dabrafenib, whereas MEK1\textsuperscript{G176S} did not alter melanoma cell sensitivity to dabrafenib (Figure 2). Based on these results, and previous reports (34, 35), we assigned MEK1\textsuperscript{K57E}, MEK1\textsuperscript{E203K} and MEK2\textsuperscript{F57C} as drivers of resistance (3 of 38, 8%) (Figure 1A). Finally, as reported previously, one Prog tumor (2%; Patient 11) carried an AKT1\textsuperscript{Q79K} activating mutation that was not present in the pre-treatment tumor (Figure 1A) (36). An AKT1\textsuperscript{A102V} mutation was detected in the Prog and matching pre-treatment tumor derived from patient 5. This AKT1 missense mutation has not been associated with AKT1 activation in cancer (COSMIC) and since the Prog displayed MAPK re-activation compared to the pre-treatment biopsy (Table 1) we did not analyze the activity of this mutation.

Mutations affecting MAPK, PI3K and cell cycle pathways

We sequenced the exomes of four matched Pre and Prog melanoma pairs, including two with unknown mechanisms of resistance (Table S1). All tumors retained the BRAF\textsuperscript{V600E} mutation (data not shown) and we identified a series of Prog-specific variants in each tumor pair (Table S2). Of these, three high-priority candidates were identified based on sequence conservation (PhyloP), predicted functional impact (SIFT) and disease association (Table S2). The MEKI\textsuperscript{E203K} and N-RAS\textsuperscript{G13R} mutations were identified in Prog tumors derived from patients 1 and 24, respectively (Table S2) and were also detected in our targeted screen (Table 1). The third candidate variant was
the pathogenic ATM<sup>R337C</sup> (37) mutation, which we confirmed by capillary sequencing (Figure S5).

Suppression of ATM expression using a highly specific shRNA, however, did not detectably alter the response of two BRAF-mutant melanoma cells to dabrafenib (Figure S5), and ATM was not attributed as a resistance mechanism. Additional analyses of our exome data did not reveal Prog-specific non-synonymous mutations affecting any of the RAS, RAF, AKT, mTOR, JAK, STAT or PI3K genes (data not shown). We identified a heterozygous nonsense mutation affecting PTEN (K221ter) and an inactivating CDKN2A/p16<sup>INK4a</sup> mutation (R80ter) in both the Pre and Prog tumors derived from patient 17 (Table S2).

**mRNA Expression Analyses and Immunohistochemistry**

The activity of the MAPK pathway was examined using two established gene transcription signatures, indicative of persistent MAPK activation (12, 29). Six Prog tumors (6/29; 21%) showed loss of MAPK activation signatures, i.e. MAPK signaling was inhibited using both MAPK activation gene sets in these progressing lesions compared with the pre-treatment tumor (Figure 3, Table S3). Five of these six MAPK-inhibited Prog tumors had no established mechanism of resistance (Table 1). A class comparison of the six MAPK-inhibited Prog tumors versus the 23 MAPK re-activated Prog tumors revealed loss of metastatic-associated gene sets, diminished epithelial-mesenchymal transition, reduced MAPK activity score and reduced proliferative signatures in the MAPK-inhibited class (Table S4).

Expression of CRAF, COT1 and PDGFRβ is upregulated at the transcript and protein levels, in a subset of BRAF-inhibitor resistant melanomas (8, 9, 12). CRAF and COT1 were not substantially increased (>3 fold) in any of the 29 Prog melanoma samples analyzed for mRNA expression, relative to the matched pre-treatment sample (Figure S6). PDGFRβ mRNA was upregulated in two Prog tumors with unknown resistance mechanisms (both from patient 3, Figure S6), but this was associated with with increased stromal, rather than tumor-specific PDGFRβ expression (Figure S7).
This suggests that tumor PDGFRβ protein overexpression was not conferring resistance in these Prog samples.

Tumors from the six patients with a MAPK-inhibited Prog tumor were examined for IGF-1R, PDGFRβ and pAKT expression. No Prog (or pre-treatment) tumors expressed PDGFRβ in melanoma cells. Immunohistochemistry analysis of IGF-1R showed increased expression in three of the six MAPK-inhibited Prog samples (patient 11 Prog 1; patient 13; patient 10 Prog 1), relative to the matched pre-treatment tumors (data not shown). Elevated IGF-1R was not associated with a corresponding increase in pAKT (17) in patient 11 and patient 13 Prog tumors, and hence IGF-1R activation was not assigned as their resistance mechanism. In patient 10, the MAPK-inhibited Prog 1 tumor stained positive for p-AKT compared with the MAPK re-activated Prog 2 tumor, and thus activation of IGF-1R/PI3K/AKT was associated with BRAF inhibitor resistance in the Prog 1 tumor (Figure S8).

**Clinical Correlates of Resistance Mechanisms and MAPK signature**

Patient clinicopathologic factors and treatment outcomes were correlated with resistance characteristics identified in the initial resected Prog tumor. Patients with multiple Progs had subsequent lesions resected after the PFS endpoint, at a median of 18.5 weeks (range 3.1-47.8) after progression.

No association was observed between specific resistance mechanisms and clinical outcome variables including the category and degree of best RECIST response (Figure 4A) or PFS (Figure 4B) (p>0.05). Similarly, there were no associations observed between the MAPK activity (re-activated versus inhibited) and clinicopathologic factors including age, sex, American Joint Committee on Cancer (AJCC) Metastases (M) stage (38), LDH, BRAF genotype, baseline RECIST sum of diameters, ECOG, the category and degree of best response (Figure 4C), and overall...
survival (all p>0.05, Table 2). However, patients with Prog tumors showing persistent MAPK inhibition had shorter PFS (Figure 4D; median 16.7 weeks vs. 30.1 weeks, p=0.01) compared with those with MAPK re-activated tumors. In multivariate PFS analysis, MAPK inhibition (HR=7.88, 95% CI: 1.95-31.78, p=0.004) and LDH (HR=3.66, 95% CI: 1.11-12.05, p=0.033) remained significant (n=20) when adjusting for additional known prognostic factors including ECOG, M stage, presence of brain metastasis, and BRAF genotype.

The median time to resection of MAPK inhibited Progs was shorter than MAPK re-activated Progs (n=21, 17.6 v 35.0 weeks, p=0.036). The behavior of the Prog tumor prior to resection (newly emerging, pre-existing and initially responded, pre-existing but never responded) did not associate with the MAPK activation signature.

**Heterogeneity of resistance mechanisms**

Six patients had multiple independent Prog tumors biopsied during the course of their BRAF inhibitor therapy. In four of these patients the lesions showed heterogeneity of known resistance mechanisms (Table S5). Patient 28 had four Prog tumors expressing various BRAF splice variants. Patients 10 and 18 each had one Prog showing MAPK inhibition (elevated IGF-1R in patient 10 Prog) and one Prog showing MAPK re-activation associated with a BRAF splice variant or MEK1K57E. Patient 11 had one Prog with an AKT1 mutation, and another Prog with no identified resistance mechanism (Table 3).

Heterogeneity of resistance was also observed within four Prog tumors. As previously reported, a single Prog tumor from patient 24 consisted of two morphologically distinct subclones, one with an N-RASG13R mutation and low p-ERK staining and the second with elevated p-ERK reactivity but no established resistance mechanism (39). A single Prog expressed two BRAF splice variants (Patient 22), another co-expressed a BRAF splice variant and an N-RAS mutation (Patient 15) and the Prog
tumor with an \textit{AKT1}^{Q79K} mutation (Patient 11, second Prog) showed MAPK signature re-activation suggesting a second unidentified MAPK reactivating mechanism of resistance was also present (Table 1).

**BRAF inhibitor resistance mechanism and subsequent response to subsequent MAPK inhibitors**

Seven of the 30 patients were subsequently treated with a MEK inhibitor or combined BRAF and MEK inhibitors after progression on single agent BRAF inhibitor, and there were no RECIST responses (Table S6) including patients with \textit{MEKI}\textsuperscript{E203K} mutation (patient 1), \textit{BRAF} amplification (patient 6), BRAF splice variant (patient 10), and \textit{N-RAS} mutation (patient 24). The lack of clinical response to subsequent MEK inhibitor therapy is inconsistent with data demonstrating that melanoma cell lines expressing \textit{BRAF} amplification (10) or \textit{BRAF} splice variants (Figure S9) are responsive to downstream MEK inhibition alone or in combination with a BRAF inhibitor.

**Discussion**

Our study confirms that MAPK signaling had been restored in 79\% of melanoma tumors resistant to dabrafenib or vemurafenib. No association was observed between the type of resistance mechanism and clinicopathologic factors, response rates or survival outcomes. Patients with MAPK re-activated Prog tumors, however, showed improved PFS, compared with patients with MAPK-inhibited resistant melanomas. This may reflect the partial cytostatic activity of BRAF inhibitors continued beyond progression in MAPK-dependent resistant melanomas (30). Despite this, seven patients progressing on BRAF inhibitor failed to respond to subsequent therapy involving a MEK inhibitor (Table S6), and at least three of these patients had melanomas with mechanisms predicted to respond to MEK inhibition (10, 12). The lack of MEK inhibitor and combination BRAF and MEK inhibitor clinical activity in patients previously treated with BRAF inhibitors (40, 41) is most likely due to the heterogeneous nature of resistance. We identified inter-tumoral heterogeneity of
resistance in all patients with multiple, independent progressing tumors with at least one identified resistance mechanism. We also observed evidence of heterogeneity within four Prog metastases (39). Although multiple mechanisms of resistance may occur within a single tumor cell, this has not been formally demonstrated and current data confirm intra-tumoral heterogeneity of resistance. For instance, only one of the two phenotypically distinct nodules within a vemurafenib-resistant tumour (patient 24) contained mutant \(N-RAS\). Similarly, two subclonal \(N-RAS\) mutations were identified within a single vemurafenib-resistant metastasis (42) and multiple mechanisms of resistance were detected, but did not co-exist, in single-cell derived dabrafenib-resistant melanoma clones (43).

Additional data, including the identification of an activating \(MEK1^{F57C}\) mutation prior to initiation of dabrafenib therapy and the appearance of multiple, independent resistant melanomas support current models that heterogeneous tumor clones exist prior to treatment initiation (44). Consequently, progression occurs when resistant tumor subclones expand under the selective pressure of BRAF inhibition and repopulate the lesion. These results suggest that adaptive clinical trials in metastatic melanoma, which involve the selection of sequential targeted drugs, based on the molecular characteristics of a single progressing biopsy, are unlikely to provide durable responses.

The relative frequency of resistance mechanisms identified in our cohort is not always consistent with previous estimates. We observed \(BRAF\) splice variants in 31% of patients and these splice variants were identical to the variants reported in vemurafenib-treated patients (32%) (15). Mutations in \(N-RAS\), identified in approximately 23% of patients with acquired resistance to vemurafenib (10, 15, 21), were far less common in our patient cohort (8%). The lower frequency of activating \(N-RAS\) mutations in dabrafenib-treated patients may correlate with the observation that patients on dabrafenib therapy develop fewer RAS-dependent squamous cell carcinomas, compared with vemurafenib-treated patients (45). It has been suggested that increased selectivity of
dabrafenib for mutant BRAF, over wild-type RAF may limit paradoxical activation of MAPK signaling (45). Paradoxical MAPK activation is dependent on RAS activity and occurs when BRAF inhibitors bind and trans-activate wild type CRAF (46-48). Vemurafenib displays similar potency against BRAF and CRAF (49), and both these kinases regulate MAPK activity in melanoma cells co-expressing BRAF\textsuperscript{V600E} and mutant N-RAS (50). Thus activation of MAPK signaling may be more pronounced in response to vemurafenib, rather than dabrafenib, in N-RAS mutant melanoma cells.

We observed BRAF copy number gains in 8% of patients. This compares to 27% of patients from a vemurafenib-treated cohort (10). Whether reported frequencies of BRAF amplification and N-RAS mutations in BRAF inhibitor resistant melanomas reflect study sample size, the distribution of biopsy sites (71% of metastases in this study were subcutaneous lesions) or genuine differences between various BRAF inhibitors requires validation.

We found MEK1 and MEK2 mutations in 7 of 38 Prog melanoma samples, but assigned resistance to only 3 (8%); MEK1\textsuperscript{K57E}, MEK1\textsuperscript{E203K} and MEK2\textsuperscript{F57C} confer resistance to BRAF inhibitors (13, 35). The contribution of MEK1 and MEK2 alterations to BRAF-inhibitor resistance has been uncertain, because the complete coding regions are not routinely screened (10, 21) and MEK1 mutations are commonly seen in both matched pre-treatment and progressing tumor samples. Functional analyses reported here and by others demonstrated that a subset of MEK mutations do not preclude a clinical response (34). We identified one patient with a MEK2\textsuperscript{F57C} mutation in the pre-treatment and progressing melanomas and this patient had a poor PFS (15.3 weeks) and OS (32.1 weeks). MEK2\textsuperscript{F57C} has been observed as a germline mutation in patients with cardio-facio-cutaneous syndrome, does not require RAF for MEK activation (51) and confers resistance to dabrafenib. Exome sequence data also identified heterozygous, nonsense mutations affecting the PTEN and CDKN2A genes in the baseline and progressing tumors of patient 17. Genetic alterations
affecting PTEN and CDKN2A are associated with poor BRAF inhibitor responses (21, 52) and patient 17 had a poor PFS (13.4 weeks).

A significant proportion (21% in this study) of BRAF inhibitor-resistant melanomas do not display MAPK re-activation, and increased IGF-1R in one such tumor is consistent with an ERK-independent resistance mechanism (17). Most of these MAPK-inhibited tumors have unknown mechanisms of resistance and show loss of metastatic, EMT and proliferative transcriptome signatures.

Several investigators have reported heterogeneity of BRAF inhibitor resistance mechanisms in subcutaneous and nodal melanoma metastases (12, 39, 42). These data indicate that selecting an effective secondary treatment, after progression on BRAF inhibitor therapy, based on the examination of a single progressing biopsy is unlikely to be effective. Accordingly, although a substantial proportion of dabrafenib- and vemurafenib-resistant melanoma patients have melanomas expressing a MEK inhibitor-sensitive BRAF slice variant (this report, (15)), the MEK inhibitor trametinib displayed minimal clinical activity as a sequential therapy either as single agent (40), or combined with dabrafenib (41). Perhaps a more accurate and complete genetic profile of patient tumors can be defined by analyzing circulating tumor cells or circulating tumor-derived DNA.

Combination therapies targeting single pathways, such as BRAF plus MEK inhibitors, are also unlikely to provide long-term disease control (53), because single mutations, such as those activating N-RAS, confer partial cross-resistance (43, 44). Anticipating the emergence of multiple resistance mechanisms by initiating drug treatments targeting multiple pathways may have more success than an adaptive sequential approach (44). For example, the simultaneous inhibition of MAPK and PI3K/mTOR activity effectively killed BRAF inhibitor-resistant melanoma cell models (54), and this strategy is being investigated in patients with BRAF mutant melanoma.
(NCT01616199, NCT01512251). Alternatively, the addition of immunotherapies (e.g. antibodies against PD1 or PD-L1) may enhance the T cell responses induced early during treatment with BRAF inhibitors (55, 56) and prolong clinical responses, and clinical trials using this approach are being planned.
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Authors Contributions

HR, RFK, RAS and GVL concept and design. HR, AMM, GMP, CF, JH, BM, TMB, SCB, JH, RS, JFT, RAS and GVL patient samples, data acquisition and experiments. HR, AMM, MSC, LEH, and GVL analyzed and interpreted the data. HR, AMM, MSC, LEH, RFK, RAS, GVL wrote the manuscript.
References

Table 1  Patient, treatment outcome and resistance characteristics

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<th>OS (weeks)</th>
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Abbreviations: dab, dabrafenib; vem, vemurafenib; PR, partial response, SD, stable disease, RES, response; PFS, progression-free survival; OS, overall survival; SQ, subcutaneous; LN, lymph node, na, data not available

* Patients without prospective RECIST assessments or measurable disease at baseline, response categorized as response (RES) or no response (no RES)

**Due to high melanin content in Prog derived RNA, only qPCR analyses of BRAF copy number was performed on this patient Prog tumor

#MAPK activity was determined using GSEA of whole transcriptome data comparing matched pre-treatment (n=21) and Prog (n=29) biopsies. + indicates re-activated, - indicates inhibited

##An AKT1 polymorphism (D46E; rs146875699) was identified in the Prog and matching pre-treatment tumors of patient 13

^ Alive at time of analysis

^^This Prog displayed two distinct subclones by p-ERK immunohistochemistry

§Patient 17 Pre and Prog tumors had nonsense mutations in the PTEN and CDKN2A genes
Table 2 Patient clinical characteristics according to MAPK activity status of Prog tumors

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<td>100%</td>
</tr>
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</table>
Abbreviations: SoD, sum of diameters; PFS, progression-free survival; OS, overall survival; AJCC, American Joint Committee on Cancer; M, metastasis.

^RECIST SoD data only available for 4 patients with MAPK inhibited Progs and 14 patients with MAPK re-activated Progs

^^Degree of best response data only available for 4 patients with MAPK inhibited Progs and 13 patients with MAPK re-activated Progs

*RECIST complete/partial response or physician assessed as response where no RECIST performed

**RECIST stable/progressive disease or physician assessed as no response where no RECIST performed
Figure Legends

Figure 1. BRAF inhibitor resistance mechanisms
(A) Mechanisms of resistance in individual Prog tumors (n=38) 
(B) Prog tumor MAPK activation status relative to the pre-treatment tumor, as determined by GSEA of gene expression data (n=29)

Figure 2. MEK1<sup>K57E</sup> and MEK2<sup>F57C</sup> confer melanoma cell resistance to dabrafenib
(A) SKMel28 melanoma cells were stably transduced with the indicated constructs. Cell lysates were analyzed for the indicated proteins 4h after incubation with dabrafenib at 0, 10, 50 and 100nM concentrations. Ectopically expressed MEK1 and MEK2 proteins were tagged with the FLAG and MYC epitopes, respectively. 
(B) Transduced SKMel28 cells were seeded at low density and 24h after seeding were treated with the indicated concentrations of dabrafenib every 72-96h. Colonies were stained with crystal violet 12 days post transduction. Photographs are representative of at least two independent transduction experiments. wt, wild type

Figure 3. Loss of MAPK activation gene sets occurs in early during treatment (EDT) responding melanoma tumors and in a subset of BRAF-inhibitor resistant Prog metastases
Box plots showing significant differences in MAPK activity (mean log2-transformed expression of MAPK activation gene transcripts) between pre-treatment (n=21) and MAPK-inhibited Prog tumors (n=6). NS, no significant differences in comparisons between pre-treatment and MAPK-reactivated Prog (n=23) tumors. Statistical comparisons between pre-treatment and EDT MAPK activity scores were not performed due to small EDT sample size (n=2). MAPK activation gene set 1 derived from (24) and gene set 2 from (14).

Figure 4. BRAF inhibitor resistance mechanisms and clinical correlates
(A) Best overall RECIST response by mechanism of resistance (n=24). Six patients excluded as they did not have RECIST assessments. Patients with multiple Prog biopsies are shown by a divided bar, and the first biopsied Prog is closest to the x-axis.

(B) Progression-free survival by mechanism of resistance (n=30). Patients with multiple biopsies are shown by a divided bar, and the first biopsied Prog is closest to the y-axis.

(C) Best overall RECIST response by MAPK activity of Prog tumors (n=17). Four patients excluded as they did not have RECIST assessments. Patients with multiple biopsies are shown by a divided bar, and the first biopsied Prog is closest to the x-axis.

(D) Progression-free survival by MAPK activity level of Prog tumors (n=21)
Figure 2

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- p-ERK\textsuperscript{Y202/204}
- ERK
- FLAG
- MEK
- β-actin

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- p-ERK\textsuperscript{Y202/204}
- ERK
- MYC
- MEK
- β-actin
Figure 3

The figure shows a box plot comparing MAPK activity scores across different conditions: Pre- and EDT (Early Drug Treatment), MAPK-activated, and MAPK-inhibited.

- **MAPK activation gene set 1** is represented by filled squares.
- **MAPK activation gene set 2** is represented by open squares.

The box plot indicates a significant difference between the groups, with a p-value of <0.001. The NS (not significant) line suggests no significant difference between the control and treatment groups.

The X-axis labels are: Pre-load, EDT, MAPK-activated, MAPK-inhibited.
Figure 4

A

Patient

Best RECIST response (% change)

-80
-60
-40
-20
0

Unknown
BRAF splice variant
MEK2
BRAF splice variant & N-RAS
MEK1
BRAF amplification
AKT1
IGF-1R

B

Patient

Progression Free Survival (weeks)

0
20
40
60
80
100

D

Progression Free Survival (%)

100
80
60
40
20
0

MAPK re-activated Prog
MAPK inhibited Prog

All Progs MAPK re-activated
At least one Prog MAPK inhibited

p=0.01
BRAF inhibitor resistance mechanisms in metastatic melanoma; spectrum and clinical impact.

Helen Rizos, Alexander M Menzies, Gulietta M Pupo, et al.

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