

Dysregulated GPCR Signaling and Therapeutic Options in Uveal Melanoma

Vivian Chua¹, Dominic Lapadula², Clinita Randolph², Jeffrey L. Benovic^{2,3}, Philip B. Wedegaertner^{2,3}, and Andrew E. Aplin^{1,3}



Abstract

Uveal melanoma is the most common primary intraocular malignant tumor in adults and arises from the transformation of melanocytes in the uveal tract. Even after treatment of the primary tumor, up to 50% of patients succumb to metastatic disease. The liver is the predominant organ of metastasis. There is an important need to provide effective treatment options for advanced stage uveal melanoma. To provide the preclinical basis for new treatments, it is important to understand the molecular underpinnings of the disease. Recent genomic studies have shown

that mutations within components of G protein-coupled receptor (GPCR) signaling are early events associated with approximately 98% of uveal melanomas.

Implications: This review discusses the alterations in GPCR signaling components (GNAQ and GNA11), dysregulated GPCR signaling cascades, and viable targeted therapies with the intent to provide insight into new therapeutic strategies in uveal melanoma. *Mol Cancer Res*; 15(5); 501–6. ©2017 AACR.

Introduction

Uveal melanoma is a rare cancer with approximately 2,500 new patient diagnoses being reported per year in the United States. Primary uveal melanoma tumors are treated effectively by radiation plaque therapy or enucleation; however, approximately 50% of patients develop metastatic disease, frequently in the liver (1, 2). In some cases, metastases are found decades after successful treatment of the primary tumors and one likely explanation is the dissemination of tumor cells from the primary site followed by cellular dormancy (3). Metastatic uveal melanoma responds poorly to clinically available therapies and patients often succumb within 1 year of diagnosis of the metastases; hence, there is an urgent unmet need for effective therapeutic strategies for advanced uveal melanoma (4). There is a low mutational burden in uveal melanoma tumors, unlike cutaneous melanoma, but identification of mutations in components of G protein-coupled receptor (GPCR) signaling in uveal melanoma tumors may uncover new therapeutic targets in uveal melanoma. These components include *GNAQ*, *GNA11*, *PLCB4*, and *CYSLTR2*, mutations of which are found in approximately 98% of uveal melanoma. Here, we review the molecular alterations in GPCR

pathway components and discuss the therapeutic possibilities directed at targeting GPCR signaling.

GNAQ and GNA11 mutations

GNAQ and *GNA11* encode the alpha subunits of guanine nucleotide-binding proteins (G proteins), $G\alpha_q$ and $G\alpha_{11}$, respectively. They form a heterotrimeric complex with β and γ subunits and are important intermediates between membrane-bound GPCRs and intracellular signaling cascades. G proteins are normally inactive when bound by guanosine diphosphate (GDP) but agonist activation of GPCRs triggers recruitment of the G proteins to the receptors where a switch from GDP to guanosine triphosphate (GTP) occurs, rendering the G proteins active to bind/stimulate proteins associated with downstream pathways. Normally, the GTPase activity of G proteins hydrolyzes GTP to GDP (5), an inactivation process that is catalyzed by the regulator of G protein signaling (RGS) proteins. *GNAQ* and *GNA11* mutations occur in a mutually exclusive manner in approximately 93% of uveal melanoma tumors [The Cancer Genome Atlas (TCGA): *GNAQ* and *GNA11* mutations detected in ~50% and ~43% of uveal melanoma tumors, respectively; ref. 6]. They are almost exclusively found in exon 5 codon 209 (Q209) although mutations in exon 4 codon 183 (R183) have been determined in a minority of cases (7–9). Common substitutions in *GNAQ* are glutamine-to-leucine (Q209L) and glutamine-to-proline (Q209P), whereas in *GNA11*, the most frequent substitution is Q209L. Q209 is crucial for the GTPase activity of G proteins; thus, hydrolysis of GTP is abolished in *GNAQ* and *GNA11* mutants, leading to constitutive activation of the $G\alpha_q$ and $G\alpha_{11}$ proteins in uveal melanoma. Interestingly, the levels of $G\alpha_q$ Q209L mutant proteins may be regulated by Ric-8A, a molecular chaperone that contributes to folding of the G protein (10). Deletion of *Ric-8A* in *GNAQ* Q209L mutant melanocytes grafted into NSG mice led to a marked reduction in levels of membrane-associated mutant $G\alpha_q$ proteins and inhibition of *GNAQ* Q209L-driven tumor progression.

¹Department of Cancer Biology, Sidney Kimmel Cancer Center at Jefferson, Thomas Jefferson University, Philadelphia, Pennsylvania. ²Department of Biochemistry and Molecular Biology, Sidney Kimmel Cancer Center at Jefferson, Thomas Jefferson University, Philadelphia, Pennsylvania. ³Cancer Cell Biology and Signaling Program, Sidney Kimmel Cancer Center at Jefferson, Thomas Jefferson University, Philadelphia, Pennsylvania.

Corresponding Author: Andrew E. Aplin, Department of Cancer Biology, Sidney Kimmel Cancer Center at Jefferson, 233 South 10th Street, Philadelphia, PA 19107. Phone: 215-503-7296; Fax: 215-923-9248; E-mail: Andrew.Aplin@kimmelcancercenter.org

doi: 10.1158/1541-7786.MCR-17-0007

©2017 American Association for Cancer Research.

Chua et al.

GNAQ and *GNA11* are the most frequently mutated genes in uveal melanoma; however, their mutations do not correlate with uveal melanoma patient outcome, patient survival, or factors that would indicate high risk of metastasis (9, 11). *GNAQ* and *GNA11* mutations occur at similar frequencies in metastasizing and nonmetastasizing tumors. Similarly, these mutations are not associated with class 1 (low metastatic potential) or class 2 (high metastatic potential) of uveal melanoma tumors (11, 12). It has been shown that the Q209 mutation in *GNAQ* and *GNA11* are found in benign nevi such as blue nevi in addition to primary and metastatic uveal melanoma tumors (7, 8). Particularly, *GNAQ* is frequently mutated in blue nevi (~83%). This suggests that mutations in the G proteins are early events in uveal melanoma development. Despite this notion, the *GNA11* Q209 mutation is more commonly identified in uveal melanoma metastases (~57%) and found only in approximately 7% of benign blue nevi, indicating that in comparison with *GNAQ*, alteration in *GNA11* is associated with higher risk of metastasis of uveal melanoma (7, 8, 13).

Effector and receptor mutations: *PLCB4* and *CYSLTR2*

In addition to the *GNAQ* and *GNA11* mutations, other, less common, driver mutations in uveal melanoma have been identified recently by next-generation sequencing. Mutations in phospholipase C β 4 (*PLCB4*) and cysteinyl leukotriene receptor 2 (*CYSLTR2*) have been identified in 1% and 4% of uveal melanoma tumors, respectively (14, 15) and are mutually exclusive with *GNAQ* and *GNA11* mutations. The alteration in *PLCB4*, D630Y, affects the Y-domain of the highly conserved catalytic core of *PLCB4* which controls signal transduction (14). Consistent with this finding, *PLCB4* interacts directly with $G\alpha_q$ (ref. 16; Fig. 1). *PLCB4* mediates signal transduction by catalyzing the conversion of phosphatidylinositol 4,5-bisphosphate (PIP2) in the plasma membrane into inositol 1,4,5-trisphosphate (IP3) and diacylglycerol (DAG). Subsequently, DAG and IP3 activate downstream signaling components such as protein kinase C (PKC). IP3, particularly, translocates into the cytosol where it induces the release of calcium (Ca^{2+}) from the endoplasmic reticulum to activate PKC.

The other alteration in the GPCR pathway in uveal melanoma is at the level of GPCRs. Out of 136 uveal melanoma patient specimens analyzed by Moore and colleagues, 4 samples harbored a leucine to glutamine substitution at codon 129 (Leu129Gln) in the *CYSLTR2* gene, and all four samples lacked mutations in *GNAQ*, *GNA11*, or *PLCB4* (15). *CYSLTR2* encodes a seven-transmembrane GPCR that activates $G\alpha_q$, a finding that is consistent with the mutual exclusive profile of the mutations (17) (Fig. 1). Activation of $G\alpha_q$ by *CysLT₂R* promotes binding of $G\alpha_q/G\alpha_{11}$ to *PLCB4*. The Leu129Gln mutation is located in the third transmembrane helix of the receptor and promotes ligand-independent activation of the GPCR. Expression of Leu129Gln *CYSLTR2* in HEK293 cells increased basal levels of calcium and promoted the growth of melanocyte cell lines *in vitro* and *in vivo* (15). Collectively, these findings raise the possibility of targeting mutant forms of *GNAQ/GNA11*, *PLCB4*, and *CYSLTR2* in uveal melanomas as well as pathways downstream of mutant *GNAQ/GNA11*.

Dysregulated pathways downstream of mutant *GNAQ/GNA11*

As the identification of mutations in GPCR signaling components in a high proportion of uveal melanoma tumors,

molecular understanding of pathways downstream of $G\alpha_q$ and $G\alpha_{11}$ has become crucial for development or discovery of effective treatment options for metastatic uveal melanoma. These pathways include the ERK1/2, Rho/Rac/YAP and PI3K/AKT pathways.

ERK1/2 pathway

The ERK1/2 pathway usually involves binding of ligands to tyrosine kinase receptors on the cell membrane and activation of downstream intermediates, RAS, RAF, and MEK. MEK phosphorylates and activates ERK1/2, which subsequently undergoes dimerization and translocates into the nucleus to regulate cellular processes including proliferation, survival, differentiation, and apoptosis (18). The ERK1/2 pathway is frequently activated in uveal melanoma with 86% of primary uveal melanoma tumors reported to have elevated ERK1/2 phosphorylation (19). However, unlike cutaneous melanoma, in which *BRAF* is commonly mutated, mutations in *RAS* and *BRAF* are rare in uveal melanoma tumors (20). Only one patient with choroidal melanoma has been shown to harbor the *BRAF* V600E mutation (21). MEK-ERK1/2 activation in uveal melanoma is expected to be induced rather by mutant $G\alpha_q/G\alpha_{11}$ proteins. The G proteins activate *PLCB* and PKC, which then stimulates MEK/ERK1/2 (ref. 18; Fig. 1). Transfection of *GNAQ* Q209L in human melanocytes enhanced phosphorylated ERK1/2 protein levels and was associated with increased anchorage-independent growth (7). Consistently, these results were reversed by siRNA-mediated knockdown of *GNAQ* which decreased phospho-ERK1/2 levels (7). However, it is noteworthy that in some uveal melanoma cases, ERK1/2 may not be activated by G proteins as a study of 22 uveal melanoma patient tumors did not observe a correlation between *GNAQ* mutation and ERK1/2 activation although samples with *GNAQ* mutations had a higher average of the total ERK1/2 expression level compared with *GNAQ* wild-type tumors (22).

Rho/Rac/YAP pathway

A major role of $G\alpha_q/11$ is to directly bind and activate *PLCB*, but additional effectors and signaling pathways may also play an important role. Particularly relevant to uveal melanoma, $G\alpha_q/11$ stimulates Rho and Rac small GTPase-mediated signaling through direct binding and activation of several members of the large Rho guanine-nucleotide exchange factor (RhoGEF) family, including p63RhoGEF and Trio (refs. 23, 24; Fig. 1). Trio appears to be a key player in mediating mitogenic signals in uveal melanoma as knockdown of Trio inhibited tumor growth and DNA synthesis in two uveal melanoma cell line models (25). Interestingly, Trio is a very large multi-domain protein that has two GEF domains, one that selectively activates RhoA and one that activates Rac1/RhoG. Notably, activation of both RhoA and Rac1 by Trio are required for $G\alpha_q/11$ mitogenic signaling (25, 26).

Multiple pathways downstream of Rho/Rac are likely to mediate Trio-dependent cell proliferation in mutant $G\alpha_q/11$ uveal melanoma cells. Depletion of Trio by siRNA did not inhibit ERK1/2 activation, but instead blocked activation of the MAPKs JNK and p38; JNK and p38 can both regulate the transcription factor AP-1 which controls the transcription of a number of growth-promoting genes (25). In addition, two reports strongly implicate two transcriptional coactivators in the Hippo pathway, Yes-associated protein (YAP) and transcriptional coactivator with PDZ-binding motif (TAZ), as being critical mediators of oncogenic $G\alpha_q/11$ downstream of Rho/Rac (27, 28). These reports

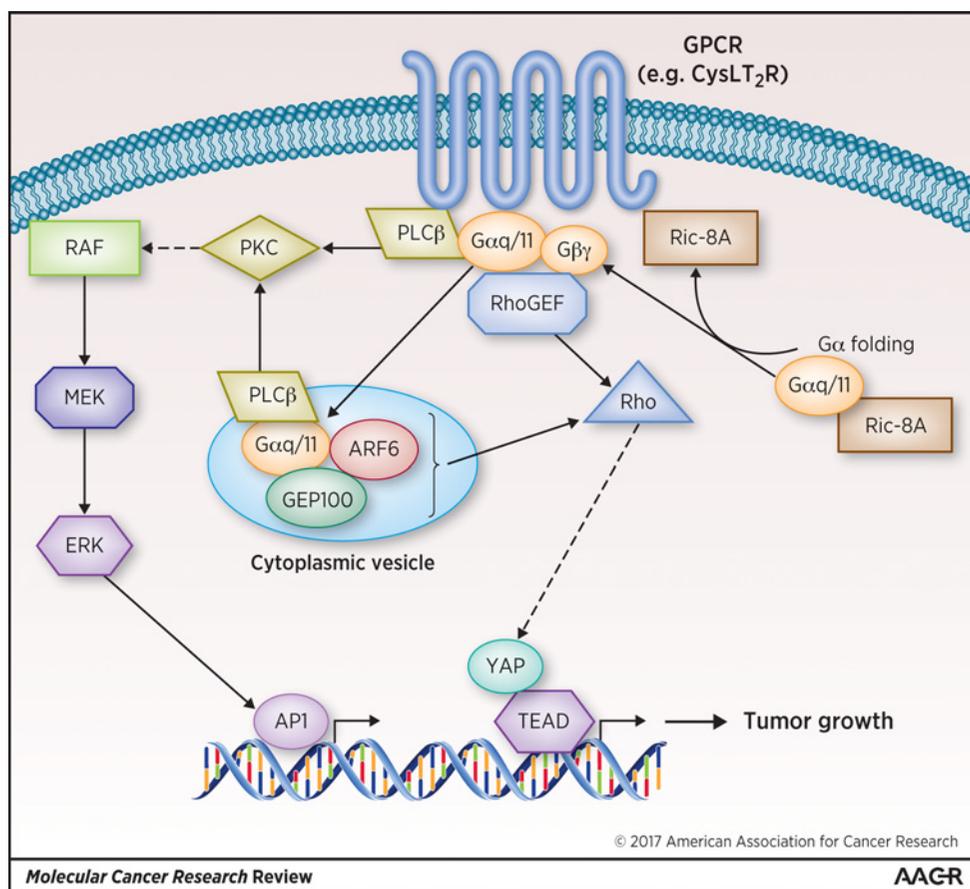


Figure 1.

Alterations in GPCR signaling in uveal melanoma. GPCRs (e.g., CysLT₂R) activate the Gα subunit proteins, Gα_q and Gα₁₁, which stimulate downstream effector pathways including ERK1/2 and YAP. Ric-8A chaperones participate in folding of G proteins which is important for membrane localization of the G proteins. ARF6 promotes localization of Gα_{q/11} to cytoplasmic vesicles where oncogenic Gα_{q/11} signaling can be active. In uveal melanoma, mutations in *GNAQ*, *GNAT1*, *CYSLTR2*, or *PLCB4* lead to constitutive activation of pathways downstream of Gα_q and Gα₁₁ proteins.

showed that mutationally activated Gα_{q/11} induced the cytoplasm to nucleus translocation of YAP/TAZ and transcription of several YAP/TAZ-dependent genes that promote cell proliferation (27, 28). Moreover, siRNA depletion of YAP or inhibition of YAP with the pharmacologic inhibitor verteporfin suppressed the growth of uveal melanoma cells in culture and in a mouse model (27, 28). Robust nuclear localization of YAP was also observed in uveal melanocytes in a recently described zebrafish model for uveal melanoma (29). The mechanisms underlying Rho and Rac activation of YAP appear to involve both inhibition of upstream kinases, large tumor suppressor homolog 1 and 2 (LATS1/2), as well as increased sequestration to F-actin of the YAP-binding protein angiomotin (AMOT), resulting in both cases in increased levels of YAP available to translocate to the nucleus (27, 28, 30). The exciting implication of the above studies is that the Trio/Rho/Rac/YAP pathway of oncogenic Gα_{q/11} signaling suggests numerous new therapeutic targets in uveal melanoma.

ADP-ribosylation factor 6 (ARF6)

Another monomeric small GTPase, ARF6, has been proposed as a key mediator of most pathways activated by oncogenic Gα_{q/11} (31). Inhibition or depletion of ARF6 in uveal melanoma cells

inhibited cell proliferation and the downstream signaling targets PLCβ, ERK1/2, Rho, Rac and YAP. Activation of ARF6 by Gα_{q/11} appears to be mediated by direct binding of Gα_{q/11} to the ARF-GEF, GEP100. A provocative mechanism for the role of ARF6 in controlling Gα_{q/11} signaling was proposed, in which ARF6 promoted localization of mutationally activated Gα_{q/11} to cytoplasmic vesicles, rather than the plasma membrane, and these cytoplasmic vesicles are the site of oncogenic signaling by Gα_{q/11} (ref. 31; Fig. 1). Regardless of the exact mechanism of how ARF6 regulates Gα_{q/11} signaling, ARF6 provides another potential therapeutic target in uveal melanoma.

PI3K/AKT pathway

Phosphatidylinositol (4,5)-bisphosphate 3-kinase (PI3K) catalyzes the formation of phosphatidylinositol (3,4,5)-trisphosphate (PIP3) from PIP2, and PIP3 induces membrane translocation of AKT where it becomes active and signals to promote cell proliferation and survival (18). PI3K signaling is negatively regulated by PTEN, which reverses PIP2 conversion to PIP3. Complete loss of PTEN is identified in 16% of uveal melanoma tumors ($n = 75$) and weaker immunostaining of PTEN is found in 42.7% of uveal melanoma tumors (32). Patients with PTEN-null tumors

Chua et al.

are associated with a shorter disease-free survival compared with patients with uveal melanoma tumors expressing normal levels of PTEN (32).

Targeted therapies in uveal melanoma

Patients with metastatic uveal melanoma typically die within one year of diagnosis; hence, there is an urgent unmet need to identify novel approaches for treatment which includes targeted therapies as either monotherapy or in combinational strategies.

GPCR inhibitors

As activating mutations in either *CYSLTR2*, *GNAQ*, *GNA11*, or *PLCB4* are found in approximately 98% of uveal melanomas, this signaling pathway represents a viable therapeutic target for the treatment of uveal melanoma. One approach to targeting this pathway is the development of specific inhibitors to individual proteins in the pathway. For example, constitutively active GPCRs such as the CysLT₂R-L129Q mutant found in uveal melanoma (15) could potentially be targeted using a receptor-specific inverse agonist, which would bind to and stabilize an inactive conformation of the receptor that should no longer activate G $\alpha_q/11$. Unfortunately, CysLT₂R-L129Q is only a viable target in approximately 4% of uveal melanoma patients. A more compelling target is the activated G protein, either G α_q or G α_{11} , which together are mutated in approximately 93% of uveal melanoma patients. In this regard, there are two potent and specific inhibitors that have been reported for G α_q , YM-254890, and FR900359 or UBO-QIC. YM-254890 is a cyclic depsipeptide isolated from *Chromobacterium* sp. broth and showed inhibition of G α_q signaling-mediated processes such as ADP-induced platelet aggregation and Ca²⁺ mobilization through a G α_q -coupled receptor (33). A crystal structure of the G α_q protein, loaded with GDP, in complex with YM-254890 suggests the inhibitor works by allosterically stabilizing the protein in the GDP-bound form, preventing GDP dissociation, and locking it in the inactive state (34). More recently, FR900359, a slightly different cyclic depsipeptide isolated from the *Ardisia crenatasims* plant, has shown similar pharmacologic activity and specificity against G α_q (35). Docking models and molecular dynamics studies suggest FR900359 inhibits G α_q in an identical manner to YM-254890 (36). While these compounds appear to be potent and selective inhibitors of G α_q (they have not been tested on G α_{11}), it is unclear whether they would be able to inhibit the constitutively active forms of G α_q typically found in uveal melanoma. For example, while YM-254890 inhibited a G α_q -R183C mutant, it was unable to inhibit G α_q -Q209L (33). Moreover, one also needs to consider G α_q versus G α_{11} selectivity when inhibiting these proteins as a nonselective G $\alpha_q/11$ inhibitor would likely be toxic, as knockout of both G α_q and G α_{11} in mice leads to death *in utero* (37). Finally, one could consider targeting PLC β 4 with a selective inhibitor as this is mutated in approximately 1% of uveal melanoma and is a downstream effector of G $\alpha_q/11$. However, PLC β 4 is unlikely to be the only downstream target of activated G $\alpha_q/11$ in uveal melanoma so such an inhibitor might only prove useful in the small number of patients that have a PLC β 4 mutation.

MEK inhibitors

Because of the high incidence of MEK-ERK1/2 activation in uveal melanoma, targeting of components of the G α_q /G α_{11} -induced ERK1/2 cascade, such as MEK and PKC, has been inves-

tigated as a therapeutic approach in uveal melanoma. Inhibition of MEK1/2 either by trametinib, selumetinib, or PD0325901 induced growth arrest and apoptosis in *GNAQ/GNA11*-mutant uveal melanoma cell lines and xenograft tumors (38–41). Trametinib is FDA-approved and is used in combination with the BRAF inhibitor, dabrafenib, for patients with unresectable or metastatic melanoma harboring BRAF V600E and V600K mutations (42). However, reports from clinical studies indicated variable outcomes for MEK inhibition in uveal melanoma. In a phase I trial involving 16 metastatic uveal melanoma patients, trametinib was shown to have limited efficacy (43). A phase II trial which enrolled 120 advanced uveal melanoma patients showed that selumetinib improved the median progression-free survival (PFS) by approximately 9 weeks compared with chemotherapy (dacarbazine or temozolomide) but only modestly increased median overall survival (44). In the most recent phase III clinical trial (SUMIT), the combination of selumetinib and dacarbazine failed to improve PFS compared with chemotherapy alone and was associated with a low response rate (3–4%; ref. 45). Thus, while preclinical studies support MEK inhibitors as part of a therapeutic approach for metastatic uveal melanoma, it is important to identify agents that in combination enhance the responses of uveal melanoma to MEK inhibition.

The poor clinical response of metastatic uveal melanoma to MEK inhibitors may be in part due to factors produced by the tumor microenvironment. Hepatocyte growth factor (HGF) provided resistance to trametinib growth-inhibitory effects in metastatic uveal melanoma cell lines and targeting of cMET (the receptor for HGF) enhanced the effects of trametinib in metastatic uveal melanoma (40, 46). HGF-cMET signaling induced downregulation of BH3 proapoptotic proteins, BIM and BCL2, which correlated with HGF-mediated inhibition of apoptosis in trametinib-treated cultures (46). Importantly, HGF is secreted by quiescent hepatic stellate cells that can be found in the liver microenvironment and phosphorylated/activated cMET is detected in the majority of uveal melanoma liver metastases (40, 46). HGF promotes activation of the PI3K/AKT pathway as a mechanism of resistance to trametinib and the increase in phosphorylation of AKT is mediated by PI3K isoforms α , δ , and γ . Use of a β -sparing PI3K inhibitor, GDC0032, reversed HGF-induced resistance to trametinib (46). These findings support an earlier study which reported the combination of MEK and PI3K inhibitors for uveal melanoma and these agents induce marked early apoptosis in *GNAQ*-mutant uveal melanoma cell lines compared with the inhibitors alone which have moderate effects on apoptosis (40, 41).

MEK inhibitors have also been tested in combination with PKC inhibitors for uveal melanoma. Inhibition of PKC alone such as by AEB071 or sotrastaurin induced cell-cycle G₁ phase arrest and suppressed PKC and ERK1/2 signaling (39). However, these effects were not durable, whereas in combination with MEK inhibitors, PD0325901, or MEK162, sustained inhibition of the ERK1/2 pathway was observed (39). Furthermore, the inhibitors caused a strong synergistic growth-inhibitory effect on uveal melanoma cell lines and marked tumor regression in uveal melanoma xenograft models. Recently, screening of drug combinations involving AEB071 in a large panel of uveal melanoma patient-derived xenografts (PDX) also determined two non-MEK inhibitors that could potentially be used in combination with PKC inhibitors as therapeutic strategies for metastatic uveal melanoma (47). These were the p53-MDM2 inhibitor, CGM097, and

the mTORC1 inhibitor, RAD001. AEB701 and CGM097 or AEB701 and RAD001 markedly reduced tumor growth and induced tumor regression (47). These studies provide evidence for a number of targeted therapies that may be evaluated in combination with MEK inhibitors or PKC inhibitors in clinical studies to improve the survival of patients with metastatic uveal melanoma.

Conclusions

There is a lack of effective treatment options for advanced uveal melanoma despite success in the treatment of primary uveal melanoma tumors. While identification of driver mutations in uveal melanoma, such as *GNAQ* and *GNA11*, has shed light on potential therapeutic targets, alterations in GPCR signaling occur early in disease progression. Other mutations and their impact on responses of uveal melanoma to GPCR-targeted therapies will need to be explored (48). For example, inactivating mutations of *BAP1* have been found in approximately 80% of aggressive uveal melanoma (49) while *SF3B1* and *EIF1AX* were shown to correlate with a favorable prognosis (50). In addition, ongoing investigations will be needed to devise strategies that elicit favorable treatment outcomes using therapies targeting GPCR signaling.

As in other forms of advanced-stage melanoma, it is likely that combination approaches will be key to elicit high response rates and the most effective combinations and scheduling of inhibitors will need to be identified.

Disclosure of Potential Conflicts of Interest

A.E. Aplin reports receiving a commercial research grant from Pfizer. No potential conflicts of interest were disclosed by the other authors.

Grant Support

Uveal melanoma research in the Aplin, Benovic, and Wedegaertner laboratories is collaboratively funded by a Dr. Ralph and Marian Falk Medical Research Trust Catalyst Award. In addition, uveal melanoma research in the Aplin lab is supported by a Melanoma Research Alliance Team Science Award, a Cure Ocular Melanoma/Melanoma Research Foundation Established Investigator Award and NIH R01 (CA182635). The Cancer Cell Biology and Signaling (CCBS) program is supported by the Cancer Center Support Grant 5P30CA056036-17. The Wedegaertner laboratory is also funded by NIH/NCI R03 CA202316-01 and a diversity supplement for NIH R01 GM56444-17 while the Benovic laboratory is also supported by NIH P01 HL114471-04.

Received January 4, 2017; revised January 31, 2017; accepted February 15, 2017; published OnlineFirst February 21, 2017.

References

- Collaborative Ocular Melanoma Study Group. Assessment of metastatic disease status at death in 435 patients with large choroidal melanoma in the Collaborative Ocular Melanoma Study (COMS): COMS report no. 15. *Arch Ophthalmol* 2001;119:670-6.
- Shields CL, Shields JA. Ocular melanoma: relatively rare but requiring respect. *Clin Dermatol* 2009;27:122-33.
- Ossowski L, Aguirre-Ghiso JA. Dormancy of metastatic melanoma. *Pigment Cell Melanoma Res* 2010;23:41-56.
- Diener-West M, Reynolds SM, Agugliaro DJ, Caldwell R, Cumming K, Earle JD, et al. Development of metastatic disease after enrollment in the COMS trials for treatment of choroidal melanoma: collaborative ocular melanoma study group report no. 26. *Arch Ophthalmol* 2005;123:1639-43.
- Markby DW, Onrust R, Bourne HR. Separate GTP binding and GTPase activating domains of a G alpha subunit. *Science* 1993;262:1895-901.
- Decatur CL, Ong E, Garg N, Anbunathan H, Bowcock AM, Field MG, et al. Driver mutations in uveal melanoma: associations with gene expression profile and patient outcomes. *JAMA Ophthalmol* 2016;134:728-33.
- Van Raamsdonk CD, Bezrookove V, Green G, Bauer J, Gaugler L, O'Brien JM, et al. Frequent somatic mutations of *GNAQ* in uveal melanoma and blue naevi. *Nature* 2009;457:599-602.
- Van Raamsdonk CD, Griewank KG, Crosby MB, Garrido MC, Vemula S, Wiesner T, et al. Mutations in *GNA11* in uveal melanoma. *N Engl J Med* 2010;363:2191-9.
- Koopmans AE, Vaarwater J, Paridaens D, Naus NC, Kilic E, de Klein A. Patient survival in uveal melanoma is not affected by oncogenic mutations in *GNAQ* and *GNA11*. *Br J Cancer* 2013;109:493-6.
- Patel BR, Tall GG. Ric-8A gene deletion or phorbol ester suppresses tumorigenesis in a mouse model of *GNAQ*(Q209L)-driven melanoma. *Oncogenesis* 2016;5:e236.
- Onken MD, Worley LA, Long MD, Duan S, Council ML, Bowcock AM, et al. Oncogenic mutations in *GNAQ* occur early in uveal melanoma. *Invest Ophthalmol Vis Sci* 2008;49:5230-4.
- Onken MD, Worley LA, Ehlers JP, Harbour JW. Gene expression profiling in uveal melanoma reveals two molecular classes and predicts metastatic death. *Cancer Res* 2004;64:7205-9.
- Griewank KG, van de Nes J, Schilling B, Moll I, Sucker A, Kavavand H, et al. Genetic and clinico-pathologic analysis of metastatic uveal melanoma. *Mod Pathol* 2014;27:175-83.
- Johansson P, Aoude LG, Wadt K, Glasson WJ, Warriar SK, Hewitt AW, et al. Deep sequencing of uveal melanoma identifies a recurrent mutation in *PLCB4*. *Oncotarget* 2016;7:4624-31.
- Moore AR, Ceraudo E, Sher JJ, Guan Y, Shoushtari AN, Chang MT, et al. Recurrent activating mutations of G-protein-coupled receptor *CYSLTR2* in uveal melanoma. *Nat Genet* 2016;48:675-80.
- Lyon AM, Tesmer JJ. Structural insights into phospholipase C- β function. *Mol Pharmacol* 2013;84:488-500.
- Evans JF. Cysteinyl leukotriene receptors. *Prostaglandins Other Lipid Mediat* 2002;68-69:587-97.
- Patel M, Smyth E, Chapman PB, Wolchok JD, Schwartz GK, Abramson DH, et al. Therapeutic implications of the emerging molecular biology of uveal melanoma. *Clin Cancer Res* 2011;17:2087-100.
- Weber A, Hengge UR, Urbanik D, Markwart A, Mirmohammadsaegh A, Reichel MB, et al. Absence of mutations of the *BRAF* gene and constitutive activation of extracellular-regulated kinase in malignant melanomas of the uvea. *Lab Invest* 2003;83:1771-6.
- Zuidervaart W, van Nieuwpoort F, Stark M, Dijkman R, Packer L, Borgstein AM, et al. Activation of the MAPK pathway is a common event in uveal melanomas although it rarely occurs through mutation of *BRAF* or *RAS*. *Br J Cancer* 2005;92:2032-8.
- Malaponte G, Libra M, Gangemi P, Bevelacqua V, Mangano K, D'Amico F, et al. Detection of *BRAF* gene mutation in primary choroidal melanoma tissue. *Cancer Biol Ther* 2006;5:225-7.
- Populo H, Vinagre J, Lopes JM, Soares P. Analysis of *GNAQ* mutations, proliferation and MAPK pathway activation in uveal melanomas. *Br J Ophthalmol* 2011;95:715-9.
- Lutz S, Freichel-Blomquist A, Yang Y, Rumenapp U, Jakobs KH, Schmidt M, et al. The guanine nucleotide exchange factor p63RhoGEF, a specific link between Gq/11-coupled receptor signaling and RhoA. *J Biol Chem* 2005;280:11134-9.
- Rojas RJ, Yohe ME, Gershburg S, Kawano T, Kozasa T, Sondke J. Galphax directly activates p63RhoGEF and Trio via a conserved extension of the Dbl homology-associated pleckstrin homology domain. *J Biol Chem* 2007;282:29201-10.
- Vaque JP, Dorsam RT, Feng X, Iglesias-Bartolome R, Forsthoefel DJ, Chen Q, et al. A genome-wide RNAi screen reveals a Trio-regulated Rho GTPase circuitry transducing mitogenic signals initiated by G protein-coupled receptors. *Mol Cell* 2013;49:94-108.
- Schmidt S, Debant A. Function and regulation of the Rho guanine nucleotide exchange factor Trio. *Small GTPases* 2014;5:e29769.

Chua et al.

27. Feng X, Degese MS, Iglesias-Bartolome R, Vaque JP, Molinolo AA, Rodrigues M, et al. Hippo-independent activation of YAP by the GNAQ uveal melanoma oncogene through a trio-regulated rho GTPase signaling circuitry. *Cancer Cell* 2014;25:831–45.
28. Yu FX, Luo J, Mo JS, Liu G, Kim YC, Meng Z, et al. Mutant Gq/11 promote uveal melanoma tumorigenesis by activating YAP. *Cancer Cell* 2014;25:822–30.
29. Mouti MA, Dee C, Coupland SE, Hurlstone AF. Minimal contribution of ERK1/2-MAPK signalling towards the maintenance of oncogenic GNAQQ209P-driven uveal melanomas in zebrafish. *Oncotarget* 2016;7:39654–70.
30. Moroishi T, Hansen CG, Guan KL. The emerging roles of YAP and TAZ in cancer. *Nat Rev Cancer* 2015;15:73–9.
31. Yoo JH, Shi DS, Grossmann AH, Sorensen LK, Tong Z, Mleynek TM, et al. ARF6 Is an actionable node that orchestrates oncogenic GNAQ signaling in uveal melanoma. *Cancer Cell* 2016;29:889–904.
32. Abdel-Rahman MH, Yang Y, Zhou XP, Craig EL, Davidorf FH, Eng C. High frequency of submicroscopic hemizygous deletion is a major mechanism of loss of expression of PTEN in uveal melanoma. *J Clin Oncol* 2006;24:288–95.
33. Takasaki J, Saito T, Taniguchi M, Kawasaki T, Moritani Y, Hayashi K, et al. A novel Galphaq/11-selective inhibitor. *J Biol Chem* 2004;279:47438–45.
34. Nishimura A, Kitano K, Takasaki J, Taniguchi M, Mizuno N, Tago K, et al. Structural basis for the specific inhibition of heterotrimeric Gq protein by a small molecule. *Proc Natl Acad Sci U S A* 2010;107:13666–71.
35. Zaima K, Deguchi J, Matsuno Y, Kaneda T, Hirasawa Y, Morita H. Vasorelaxant effect of FR900359 from *Ardisia crenata* on rat aortic artery. *J Nat Med* 2013;67:196–201.
36. Schrage R, Schmitz AL, Gaffal E, Annala S, Kehraus S, Wenzel D, et al. The experimental power of FR900359 to study Gq-regulated biological processes. *Nat Commun* 2015;6:10156.
37. Offermanns S, Zhao LP, Gohla A, Sarosi I, Simon MI, Wilkie TM. Embryonic cardiomyocyte hypoplasia and craniofacial defects in G alpha q/G alpha 11-mutant mice. *EMBO J* 1998;17:4304–12.
38. Ambrosini G, Musi E, Ho AL, de Stanchina E, Schwartz GK. Inhibition of mutant GNAQ signaling in uveal melanoma induces AMPK-dependent autophagic cell death. *Mol Cancer Ther* 2013;12:768–76.
39. Chen X, Wu Q, Tan L, Porter D, Jager MJ, Emery C, et al. Combined PKC and MEK inhibition in uveal melanoma with GNAQ and GNA11 mutations. *Oncogene* 2014;33:4724–34.
40. Cheng H, Terai M, Kageyama K, Ozaki S, McCue PA, Sato T, et al. Paracrine effect of NRG1 and HGF drives resistance to MEK inhibitors in metastatic uveal melanoma. *Cancer Res* 2015;75:2737–48.
41. Khalili JS, Yu X, Wang J, Hayes BC, Davies MA, Lizee G, et al. Combination small molecule MEK and PI3K inhibition enhances uveal melanoma cell death in a mutant GNAQ- and GNA11-dependent manner. *Clin Cancer Res* 2012;18:4345–55.
42. Flaherty KT, Infante JR, Daud A, Gonzalez R, Kefford RF, Sosman J, et al. Combined BRAF and MEK inhibition in melanoma with BRAF V600 mutations. *N Engl J Med* 2012;367:1694–703.
43. Falchook GS, Lewis KD, Infante JR, Gordon MS, Vogelzang NJ, DeMarini DJ, et al. Activity of the oral MEK inhibitor trametinib in patients with advanced melanoma: a phase 1 dose-escalation trial. *Lancet Oncol* 2012;13:782–9.
44. Carvajal RD, Sosman JA, Quevedo JF, Milhem MM, Joshua AM, Kudchadkar RR, et al. Effect of selumetinib vs chemotherapy on progression-free survival in uveal melanoma: a randomized clinical trial. *JAMA* 2014;311:2397–405.
45. Carvajal RD, Schwartz GK, Mann H, Smith I, Nathan PD. Study design and rationale for a randomised, placebo-controlled, double-blind study to assess the efficacy of selumetinib (AZD6244; ARRY-142886) in combination with dacarbazine in patients with metastatic uveal melanoma (SUMIT). *BMC Cancer* 2015;15:467.
46. Cheng H, Chua V, Liao C, Purwin TJ, Terai M, Kageyama K, et al. Co-targeting HGF-cMET signaling with MEK inhibitors in metastatic uveal melanoma. *Mol Cancer Ther* 2017;16:516–28.
47. Carita G, Frisch-Dit-Leitz E, Dahmani A, Raymondie C, Cassoux N, Piperno-Neumann S, et al. Dual inhibition of protein kinase C and p53-MDM2 or PKC and mTORC1 are novel efficient therapeutic approaches for uveal melanoma. *Oncotarget* 2016;7:33542–56.
48. Harbour JW, Chao DL. A molecular revolution in uveal melanoma: implications for patient care and targeted therapy. *Ophthalmology* 2014;121:1281–8.
49. Harbour JW, Onken MD, Roberson ED, Duan S, Cao L, Worley LA, et al. Frequent mutation of BAP1 in metastasizing uveal melanomas. *Science* 2010;330:1410–3.
50. Martin M, Masshofer L, Temming P, Rahmann S, Metz C, Bornfeld N, et al. Exome sequencing identifies recurrent somatic mutations in EIF1AX and SF3B1 in uveal melanoma with disomy 3. *Nat Genet* 2013;45:933–6.

Molecular Cancer Research

Dysregulated GPCR Signaling and Therapeutic Options in Uveal Melanoma

Vivian Chua, Dominic Lapadula, Clinita Randolph, et al.

Mol Cancer Res 2017;15:501-506. Published OnlineFirst February 21, 2017.

Updated version Access the most recent version of this article at:
doi:[10.1158/1541-7786.MCR-17-0007](https://doi.org/10.1158/1541-7786.MCR-17-0007)

Cited articles This article cites 50 articles, 17 of which you can access for free at:
<http://mcr.aacrjournals.org/content/15/5/501.full#ref-list-1>

Citing articles This article has been cited by 4 HighWire-hosted articles. Access the articles at:
<http://mcr.aacrjournals.org/content/15/5/501.full#related-urls>

E-mail alerts [Sign up to receive free email-alerts](#) related to this article or journal.

Reprints and Subscriptions To order reprints of this article or to subscribe to the journal, contact the AACR Publications Department at pubs@aacr.org.

Permissions To request permission to re-use all or part of this article, use this link
<http://mcr.aacrjournals.org/content/15/5/501>.
Click on "Request Permissions" which will take you to the Copyright Clearance Center's (CCC) Rightslink site.