Mutant Gq/11 Promote Uveal Melanoma Tumorigenesis by Activating YAP

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SUMMARY

Uveal melanoma (UM) is the most common cancer in adult eyes. Approximately 80% of UMs harbor somatic activating mutations in GNAQ or GNA11 (encoding Gq or G11, respectively). Herein, we show in both cell culture and human tumors that cancer-associated Gq/11 mutants activate YAP, a major effector of the Hippo tumor suppressor pathway that is also regulated by G protein-coupled receptor signaling. YAP mediates the oncogenic activity of mutant Gq/11 in UM development, and the YAP inhibitor verteporfin blocks tumor growth of UM cells containing Gq/11 mutations. This study reveals an essential role of the Hippo-YAP pathway in Gq/11-induced tumorigenesis and suggests YAP as a potential drug target for UM patients carrying mutations in GNAQ or GNA11.

INTRODUCTION

Uveal melanoma (UM) is the most common intraocular tumor in adults and accounts for ~5% of all melanomas (Singh et al., 2005). UM frequently metastasizes to the liver along a hematogenous route, as 90% of UM metastasis is found in the liver. Once metastasized, there is no effective therapy, with average survival of 2 to 8 months (Singh et al., 2005). Unlike cutaneous melanoma, UM originates from melanocytes of the choroid, ciliary body, and iris (collectively known as the uvea) derived from the neural crest (Arnesen, 1985).

Molecular genetic analyses have shown that the mutational spectrum of UM is very different from that of cutaneous melanoma. Instead of the BRAF or NRAS mutations common in cutaneous melanoma, more than 80% of UMs carry activating mutations in either GNAQ or GNA11 (Lamba et al., 2009; Van Raamsdonk et al., 2009, 2010). Only UM derived from the iris, a minor fraction (5%) of total UM cases, harbors BRAF mutations.

Significance

UM is the most common type of adult eye cancer. Currently there is no effective treatment, especially for metastatic UM. Most UMs have activating mutations in one of two homologous G proteins, Gq or G11 (encoded by GNAQ or GNA11, respectively). We found that the Hippo pathway effector YAP is activated in UM containing mutant Gq/11, and inhibition of YAP by either genetic or pharmacological approaches blocks tumor growth of Gq/11-mutated UM cells in mouse models, suggesting a strategy for UM intervention by inhibiting YAP. This mechanism, whereby YAP activation mediates mutant Gq/11 signaling in tumorigenesis, may serve as a paradigm for general pathogenesis of human cancers with aberrant expression or mutations of G protein-coupled receptor or G proteins.
The Q209L mutation), but not the wild-type, is able to stimulate
whereas activation of Gs inhibits YAP by increasing YAP phos-
in a manner dependent on the coupled G protein. For example,
man embryonic kidney 293A (HEK293A) cells, ectopic expres-
GNA11
hot spot mutations found in UM on YAP activity. In hu-
malignant UM (Van Raamsdonk et al., 2010). R183 and Q209 are located in the switch I and
switch II domains of Gq/11 proteins, respectively, and these mu-
tations convert the G proteins into a constitutively active form by
decreasing their guanosine triphosphatase activity. Therefore,
the cancer-associated mutant Gq/11 would induce constitutive
downstream signaling that presumably contributes to tumor
development.

Previous work has shown that overexpression of active Gq/11
can induce transformation of normal melanocytes (Van Raams-
donk et al., 2009, 2010). Moreover, downregulation of mutant
Gq/11 in UM cells abolished their ability to form tumors in immu-
nocompromised mice, demonstrating a direct cancer-driving
function of the active Gq/11 in tumorigenesis (Van Raamsdonk
et al., 2009, 2010). Although it has been proposed that Gq/11
activates the MAP kinase, the precise molecular mechanism of
these activating Gq/11 mutations in UM development remains
to be defined.

The Hippo tumor suppressor pathway normally functions
to control tissue homeostasis and limit organ size (Halder and
Johnson, 2011; Pan, 2010; Tapon and Harvey, 2012; Yu and
Guan, 2013). Core components of the Hippo pathway are repre-
sented by a kinase cascade consisting of MST1/2 and Lats1/2. The Lats1/2 kinases phosphorylate and inactivate YAP and
TAZ, two homologous transcription coactivators with oncogenic
potential. In fact, elevated expression or nuclear enrichment of
YAP/TAZ has been observed in multiple types of human cancers
(Chan et al., 2008; Steinhardt et al., 2008; Zhao et al., 2007). We
recently reported that the Hippo pathway is strongly regulated by
GPCR signaling (Miller et al., 2012; Mo et al., 2012; Yu et al.,
2012). GPCR signaling can either activate or inhibit YAP activity
in a manner dependent on the coupled G protein. For example,
activation of G12/13 stimulates YAP by inducing YAP dephos-
phorylation, nuclear localization, and transcriptional activity,
whereas activation of Gs inhibits YAP by increasing YAP phos-
phorylation. Interestingly, expression of active Gq/11 (containing
the Q209L mutation), but not the wild-type, is able to stimulate
YAP/TAZ dephosphorylation (Yu et al., 2012), indicating that
YAP can be activated by Gq/11. These observations prompted us
to investigate if the Hippo-YAP pathway might function as a
mediator in active Gq/11-induced tumorigenesis, particularly in
UM development.

RESULTS

Activation of YAP by Mutant Gq/11 in UM
To test whether YAP can be activated by the cancer-associated
mutant Gq/11, we first determined the effects of GNAQ and
GNA11 hot spot mutations found in UM on YAP activity. In hu-
man embryonic kidney 293A (HEK293A) cells, ectopic expres-
sion of mutant Gq/11 (GqR183Q, GqQ209L, or G11Q209L), but not
the wild-type Gq or G11, caused a dramatic dephosphorylation of
cotransfected YAP, as indicated by faster migration of YAP
on a phos-tag-containing gel (Figure 1A). Because phosphoryla-
tion inhibits YAP, these data suggest that mutant Gq/11 acti-
vates YAP. TAZ has two phosphodegrons and Lats-induced
phosphorylation promotes TAZ ubiquitination and degradation
(Huang et al., 2012; Liu et al., 2010). As expected, the endoge-
nous TAZ protein levels were significantly increased in the pres-
uence of mutant Gq/11 (Figure 1A). Lats-induced phosphorylation
inhibits YAP/TAZ by promoting YAP/TAZ cytoplasmic seques-
tration, while dephosphorylated YAP/TAZ translocate to the
nucleus and stimulate gene expression. Consistently, overex-
pression of active Gq/11 mutants, but not wild-type Gq/11,
induced nuclear localization of endogenous YAP/TAZ, as as-
essed by immunofluorescence staining with an antibody that
recognizes both YAP and TAZ (Figures S1A–S1C available on-
one). These results show that the mutant Gq/11 found in UM
together activates YAP/TAZ and suggest a model that activation
of YAP/TAZ may contribute to mutant Gq/11-induced UM de-
velopment, given the known oncogenic function of these two tran-
scription coactivators.

We then investigated YAP/TAZ activation status in a panel
of 13 cell lines established from primary or metastatic UM
by different laboratories. We sequenced the genes of GNAQ
and GNA11. Among these UM cell lines, seven (92.1, Mel202,
Mel270, OMM1.3, OMM2.2, OMM2.3, and OMM2.5) contain
the GqQ209L mutation, one (OMM1) contains the G11Q209L
mutation, and the remaining five tumor lines (OCM1, OCM3,
OCM8, Mel285, and Mel290) have no mutations in Gq/11 (Figure 1B).
These data are consistent with other recently reported mutation
analyses, and among these cell lines, three (OCM1, OCM3,
and OCM8) contain BRAFV600E mutations (Griewank et al., 2012).
Next, we determined YAP/TAZ phosphorylation and subcellular
localization for each of these UM cell lines. Interestingly, all
UM cell lines with Gq/11 mutations displayed low or moderate YAP
phosphorylation and strong nuclear YAP (or YAP/TAZ)
localization (Figure 1B). On the other hand, YAP was highly phos-
phorylated and exhibited exclusive cytoplasmic localization in
BRAF-mutant cells (Figure 1B). These observations demonstrate
that YAP is activated in Gq/11-mutant UM cells but inactivated in
BRAF-mutant cells.

YAP/TAZ are known to be activated by serum or lysophospha-
tidic acid (LPA) (Miller et al., 2012; Yu et al., 2012). Both serum
and LPA activate YAP/TAZ by inducing rapid dephosphorylation
and nuclear localization. In UM cells with wild-type Gq/11 and
BRAF, serum and LPA induced a strong YAP dephosphorylation
and concomitantly increased YAP nuclear localization (Figures
1B–1D; Figures S1D and S1E). In contrast, in UM cells containing
mutated Gq/11, YAP was dephosphorylated and localized in the
nucleus regardless of the serum or LPA conditions. Our findings
show that YAP/TAZ are indeed more active in UM cell lines con-
aining Gq/11 mutations and are no longer sensitive to serum or
LPA. Notably, in UM cells with mutant BRAF, YAP was heavily
phosphorylated, and the serum and LPA-induced YAP dephos-
phorylation and nuclear localization were blunted (Figures
1B–1D; Figures S1D and S1E). In support, Lats phosphorylation
status, an indicator of kinase activity, was higher in BRAF-mutant
cells than in Gq/11-mutant cells (Figure S1F). These data
suggest that YAP activation is not needed for tumor growth of BRAF-mutant cells, and moreover, active BRAF might suppress YAP activation.

Previously, Gq/11 mutant-induced activation of the extracellular-signal-regulated kinases (ERKs), also known as MAP kinase; Nuc, nucleus; WT, wild-type. The number of plus signs indicates the strength. *Information from Griewank et al. (2012). pERK1/2 + + ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ --
Downregulation of Gq in UM Cells Inactivates YAP
In a subcutaneous xenograft mouse model, 92.1 (GqQ209L) cells transfected with small hairpin RNA (shRNA) targeting Gq failed to develop tumor (Figure 3A), confirming an essential role for mutant Gq in tumorigenesis of 92.1 cells. We tested whether the mutant Gq is required for high YAP activity in UM cells. In both 92.1 and Mel270 (GqQ209R) cells, we established stable lines expressing control shRNA or Gq shRNAs (#1 and #2 target different regions). Knockdown of Gq was confirmed by western blotting (Figure 3B). We observed that YAP phosphorylation (as indicated by the phosphorylated YAP western blot) was increased in cells expressing Gq shRNA (Figure 3B). When dephosphorylated, YAP localizes in the nucleus and interacts with the TEAD family of transcription factors to stimulate gene transcription (Cao et al., 2008; Wu et al., 2008; Zhang et al., 2008; Zhao et al., 2008). We examined the interaction of YAP with TEAD. In Gq-knockdown cells, the interaction of YAP and TEAD was decreased, whereas Gq knockdown had no effect on TEAD1 expression (Figure 3C). In addition, YAP nuclear localization was decreased in Gq-knockdown cells (Figures 3D and 3E), consistent with YAP inactivation. We have recently shown that Gs-protein kinase A (PKA) signaling stimulates YAP/TAZ phosphorylation, an effect opposite to Gq/11 activation (Kim et al., 2013; Yuet et al., 2013; Yu et al., 2012). As expected, YAP phosphorylation was increased in 92.1 cells when treated with forskolin and 3-isobutyl-1-methylxanthine (IBMX), which increase cyclic AMP and activate PKA (Figure 3F). Notably, forskolin and IBMX induced stronger YAP phosphorylation in the Gq-knockdown 92.1 cells (Figure 3F), indicating that the active mutant Gq in 92.1 cells functions antagonistically to PKA. The above data support a function for mutant Gq in maintaining YAP in a dephosphorylated and activated status in UM cells.

YAP Is Required for Mutant Gq/11, but Not Mutant BRAF, Driving Tumorigenesis
Expression of active Gq/11 (Q209L) in immortalized melanocytes (melan-a cells) is sufficient to induce cell transformation (Van Raamsdonk et al., 2009, 2010). This offers a well-defined and cleaner system for functional studies than UM-derived cell lines, which certainly contain mutations besides Gq/11. In melan-a cells expressing GqQ209L or G11Q209L, YAP phosphorylation was reduced (Figures S2A and S2B), and the YAP-TEAD interaction was increased (Figure S2C), indicating higher YAP activity. To test the role of YAP/TAZ in GqQ209L-induced cell transformation, we generated GqQ209L-stable melan-a cells expressing control, YAP, and/or TAZ shRNAs (Figure 4A). As an indicator of transformation, GqQ209L-stable melan-a cells, but not control melan-a cells expressing GFP, could support anchorage-independent growth in soft agar. Importantly, GqQ209L-stable melan-a cells expressing YAP and/or TAZ shRNAs failed to form colonies (Figures 4B; Figure S2D). In addition, when subcutaneously grafted into nude mice, GqQ209L-stable melan-a cells with YAP knockdown exhibited a significant reduction in tumor growth (Figures 4C; Figure S2H). These results indicate that YAP/TAZ are important for Gq-induced neoplastic transformation.

To investigate the role of YAP in the tumorigenesis of UM-derived cell lines, we attempted to knock down YAP in 92.1 cells (GqQ209R), which have high YAP activity, and OCM1 (BRAFV600E) cells, which have low YAP activity. Although it was easy to knock down YAP in OCM1 cells, we failed to establish an efficient YAP knockdown in 92.1 cells (data not shown). These observations suggest a critical role for YAP in 92.1 cell proliferation, which may be addicted to high YAP activity. We then made an inducible shRNA (pTRIPZ system) containing the same YAP targeting sequences used in the conventional vector (pLKO.1) and successfully established both 92.1 and OCM1 stable cells. YAP expression in these cell lines was effectively reduced upon doxycycline (Dox) treatment that induced expression of the shRNAs (Figure 4D). In vitro, the proliferation of 92.1 cells was slightly reduced upon Dox treatment, whereas knockdown of YAP in OCM1 cells showed no significant effect on cell proliferation (Figures S2E and S2F). We also assessed the cell-migratory
Roles of the Hippo-YAP Pathway in Uveal Melanoma

The YAP-Inhibitory Drug Verteporfin Selectively Suppresses Gq/11-Mutant UM Tumorigenesis

The strong correlation between the Gq/11 mutation and YAP activation in UM specimens and UM cell lines and the effectiveness of YAP knockdown in preventing tumor growth of Gq/11-mutated UM cells in a mouse xenograft model prompted us to test the effect of pharmacological inhibition of YAP on the tumorigenesis of UM cells. It has recently been reported that the porphyrin-family compounds, such as verteporfin, disrupt the YAP-TEAD interaction and therefore inhibit the function of YAP in liver size control (Liu-Chittenden et al., 2012). Verteporfin is a drug with Food and Drug Administration (FDA) approval for photodynamic therapy to eliminate abnormal blood vessels in the eye (Bressler and Bressler, 2000). Interestingly, when treated with verteporfin, the UM cells with Gq/11 mutations were effectively killed, as indicated by the cleavage of poly (ADP-ribose) polymerase-1 (PARP1, an apoptosis marker; Figure 5A; Figure S3A). Similarly, the Gq/11-mutant UM cells were sensitive to growth inhibition by verteporfin (Figure S3B). In comparison, the BRAF-mutant cells were more resistant to both growth inhibition and apoptosis in response to verteporfin treatment (Figure 5A; Figures S3A and S3B). On the other hand, the BRAF-mutant UM cells were more easily killed by U0126 (an inhibitor for MAP kinase kinase [MEK], the ERK-activating kinase), while the Gq-mutant cells were resistant to U0126 (Figure 5B). These results suggest a model in which YAP activation is more important for Gq/11-mutant tumor cells, whereas ERK activation is more important for BRAF-mutant tumor cells. Our data indicate that verteporfin may be used to selectively kill tumor cells with elevated YAP activity, such as UM containing mutations in Gq/11.

To assess the role of verteporfin in inhibiting tumorigenesis of UM cells, we used an orthotopic mouse model. Tumor cells were injected into the suprachoroidal space of the eye of the severe combined immunodeficient (SCID) mice. Tumor formation was monitored by noninvasive fundus examinations and optical coherence tomography (OCT) in live animals and histological analyses after mice were euthanized (Figures S3C and S3D). Aggressive endophytic growth was seen in 92.1 cells, resulting in filling of the inside of the eye with tumor cells (Figures S3C and S3D). We investigated the effect of verteporfin on the inhibition of tumor growth in vivo. Clinical-grade verteporfin (40 μg/injection) was packaged into nanoparticles and mixed with 92.1, Mel270, or OCM1 cells prior to injection into the eye. As negative controls, UM cells were coinjected with empty nanoparticles. For the verteporfin-treated group, mice were also administered 100 mg/kg verteporfin along an intraperitoneal route every other day over a period of 14 days, whereas control mice were injected with PBS. After 6 weeks, compared with the control group, verteporfin treatment significantly reduced tumor growth of the Gq mutant 92.1 and Mel270 cells (Figures 5C and 5D; Figures S3E and S3F). In contrast, verteporfin treatment had little effect on tumor growth of the BRAF-mutant OCM1 cells (Figures 5E and 5F). Therefore, these mouse model studies demonstrate that
verteporfin is effective in inhibiting tumor cell growth and might be considered for targeted treatment of UM with Gq/11 mutations and elevated YAP activity.

DISCUSSION

UM is the most common intraocular tumor in adults and frequently metastasizes to the liver. Early-stage UM can be treated by radiation or enucleation (removal of the eye), but there is no effective treatment for metastatic UM, which is the most feared complication and the main cause of death (Singh et al., 2005). Enucleation has been the last resort to prevent metastasis and has a long-lasting adverse and psychological impact on patients, even though enucleation does not significantly improve the outcome of survival (Collaborative Ocular Melanoma Study Group, 1998). Therefore, a systemic treatment of metastasis is urgently needed. The high penetrance of Gq/11-activating mutations and the essential role of mutant Gq/11 in UM oncogenesis warrants the need for an in-depth mechanistic understanding of Gq/11 in tumorigenesis. Moreover, the establishment of mutant Gq/11 as a cancer driver suggests a potential of developing targeted therapies for UM treatment. Unfortunately, a drug that targets constitutively active Gq/11 is currently not available. It is therefore important to identify downstream effectors essential for Gq/11-induced tumorigenesis, and these effectors may provide opportunities to develop molecular-targeted drugs for UM management.

In this report, we reveal a strong correlation between Gq/11 mutations and YAP activation in UM. We have established a causal relationship between Gq/11 mutation and YAP activation, and we show that YAP is essential in transducing the oncogenic activity of mutant Gq/11 to induce UM. Thus, YAP may serve as a drug target for pharmaceutical intervention of UM. Indeed, this concept is strongly supported by our data showing that downregulation of YAP selectively inhibits tumor growth of UM cells containing mutated Gq/11. Furthermore, verteporfin inhibits the proliferation of UM cells with Gq/11 mutations in vitro and is effective in suppressing their growth in a mouse model. Verteporfin is already an FDA-approved drug for eye disease indications such as macular degeneration, so it would be relatively easy to adapt this drug for UM treatment. Hence, the result of UM inhibition by verteporfin offers exciting possibilities not...
BRAFV600E mutant melanoma. Our study indicates that YAP activation is an effective target-based therapy commonly used to treat Gq/11-mutant UM cells. The mechanism-based inhibition of the Gq/11-mutant UM cells is due to general toxicity but rather target specific and mechanism-based inhibition of the Gq/11-mutant UM cells are not required for verteporfin to inhibit neovascular angiogenesis but is not required to disrupt the interaction between YAP and TEAD (Liu-Chittenden et al., 2012). Therefore, verteporfin could have a dual function, inhibiting angiogenesis and YAP activity, both of which can positively contribute to inhibiting UM. Our data indicate that verteporfin should be considered for UM treatment. It is equally important to note that verteporfin is ineffective toward tumors in the verteporfin treatment group (C, right) were smaller, as indicated by black arrows. The tumor areas from five injected eyes were quantified and are shown in (D). (E and F) Effect of verteporfin treatment on tumor growth of OCM1 cells. Similar experiments were performed as in (C) and (D) using OCM1 cells. Student’s t test (two tailed, 95% confidence intervals) was used for statistical analysis, and error bars represent SD. The scale bars represent 100 μm.

Figure 5. YAP Inhibitor Suppresses Tumor Growth of Gq/11-Mutated UM Cells

(A) Sensitivity of Gq/11-mutant and BRAF-mutant UM cells to verteporfin, a YAP inhibitor. Gq-mutant cells or BRAF-mutant cells were treated with 0.2 or 1 μg/ml of verteporfin for 48 hr, and cell lysates were assessed for PARP1 cleavage (the black arrow indicates the position of cleaved PARP1, an indicator of cell death). (B) Sensitivity of Gq/11-mutant and BRAF-mutant UM cells to U0126, a MEK inhibitor. UM cells were treated with 5 and 25 μM of U0126 for 36 hr, and then cell apoptosis was assessed by PARP1 cleavage.

Only for the treatment of local intraocular UM but also for deadly metastasis. Notably, the FDA-approved application of verteporfin is based on photodynamic therapy to eliminate neovascularization of blood vessels. Light activation of the drug is required for verteporfin to inhibit neovascular angiogenesis but is not required to disrupt the interaction between YAP and TEAD (Liu-Chittenden et al., 2012). Therefore, verteporfin could have a dual function, inhibiting angiogenesis and YAP activity, both of which can positively contribute to inhibiting UM. Our data indicate that verteporfin should be considered for UM treatment. It is equally important to note that verteporfin is ineffective toward the BRAF-mutant UM cells, which are sensitive to MEK inhibitors. These observations suggest that the therapeutic effects of verteporfin observed on the Gq/11-mutant UM cells are not due to general toxicity but rather target specific and mechanism-based inhibition of the Gq/11-mutant UM cells.

It has been previously shown that the active Gq/11 mutant also stimulates the ERK pathway (Van Raamsdonk et al., 2009, 2010). This is not surprising, because G proteins are known to initiate multiple downstream signaling events. However, activation of the ERK pathway by active Gq/11 is less potent compared with that of the BRAF<sup>V600E</sup> mutation, which is frequently found in cutaneous melanoma (Figure 1B; Figure S1D). BRAF inhibition is an effective target-based therapy commonly used to treat BRAF<sup>V600E</sup> mutant melanoma. Our study indicates that YAP activation is more important than ERK activation in UM. Consistent with this notion, downregulation of YAP or verteporfin treatment induces more cell death and tumor inhibition in Gq/11-mutant UM cells than in BRAF-mutant UM cells (Figures 4F–4H and 5).

Further studies are needed to determine the effect of a combined treatment inhibiting both MEK and YAP in treating UM with the Gq/11 mutation.

YAP/TAZ are frequently activated in human cancers (Harvey et al., 2013). However, the underlying mechanisms leading to YAP/TAZ activation in cancers are largely unknown. Mutations in the Hippo pathway components are rare in human cancers. One notable example is the neurofibromin 2 (NF2) tumor suppressor. Mutation in NF2 activates YAP, and YAP activation is required for NF2-induced tumorigenesis (Zhang et al., 2010). Our report not only reveals a mechanism of YAP activation in Gq/11-induced tumorigenesis but also suggests that YAP activation plays a critical role in cancer development with altered GPCR signaling. In addition to UM, other types of neoplastic lesions, such as blue nevi (Van Raamsdonk et al., 2009) and leptomeningeal melanocytic lesions (Küsters-Vandevelde et al., 2010) also contain prevalent Gq/11 mutations. More recently, the GqR183Q mutation has been identified in 80% to 90% of Sturge-Weber syndrome and port-wine stain patients (Shirley et al., 2013). We also showed that GqR183Q also potently activated YAP (Figure 1A; Figures S1A–S1C). Interestingly, most of
these tumors or overgrowths, including those caused by NF2 loss-of-function mutations, are derived from the neuroectoderm. Activation of YAP/TAZ by Gq/11 or NF2 mutations in these tumors suggests that the Hippo pathway plays an important role in the development and differentiation of the neuroectoderm, consistent with a role of the Hippo pathway in regulating neural progenitor cells (Cao et al., 2008).

GPCRs constitute the largest family of cell surface receptors encoded by the human genome. Although cancer-associated mutations in GPCR signaling are less frequent than receptor tyrosine kinases, extensive cancer genome sequencing has revealed that approximately 20% of all human cancers may have altered GPCR signaling (O’Hayre et al., 2013). For example, mutation of metabotropic glutamate receptor occurs at an appreciable frequency in cutaneous melanoma (Prickett et al., 2011). Besides genetic alterations (mutation or amplification), GPCRs are stimulated by their cognate ligands, and therefore altered ligand levels can also lead to abnormal GPCR signaling. For example, LPA is a potent mitogen and strongly activates YAP/TAZ (Miller et al., 2012; Yu et al., 2012). In fact, LPA is elevated and defined as a biomarker for ovarian cancer (Mills and Mooney, 2003). We have recently shown that YAP is broadly regulated by a large number of GPCRs (Yu et al., 2012). Collectively, these observations suggest a potential paradigm that YAP activation plays a broad role in cancers driven by altered GPCR signaling, and thus YAP inhibitors, such as verteporfin, represent a potential therapeutic for cancers with altered GPCR signaling.

EXPERIMENTAL PROCEDURES

More experimental procedures are shown in the Supplemental Information.

Cell Culture

UM cell lines, provided by Dr. Martine Jager (Leiden University), were maintained in RPMI 1640 medium with 10% fetal bovine serum (FBS). Melan-a cells, a gift from Dr. Dorothy Bennett (St. George University), were cultured in RPMI medium with 10% FBS and 200 μM 12-O-tetradecanoylphorbol-13-acetate. HEK293A, human embryonic kidney 293T, and human embryonic kidney 293P cells were cultured in Dulbecco’s modified Eagle’s medium with 10% FBS. All media were supplemented with 50 μg/ml penicillin/streptomycin.

Animal Work

All animal procedures were carried out according to protocols approved by the Institutional Animal Care and Use Committee of the University of California, San Diego. For subcutaneous xenograft experiments, 12-week-old male nude mice were used. Cells (melan-a, 92.1, OCM1, or OCM8) with manipulations of YAP or Gq expression were grafted subcutaneously into both flanks of mice, and tumor growth was monitored three times a week. Mice were euthanized after 10 weeks of cell injection or until the tumor size reached 1 cm³ to document the formation of primary tumors. For the orthotopic UM mouse model, male 4-week-old SCID mice were used. Mice were anesthetized, and 50,000 cells of 92.1, Mel270, or OCM1 were injected into the suprachoroidal space in the right eye using a 33-gauge needle. Tumor formation was monitored every week by fundus examinations and OCT (Spectralis; Heidelberg Engineering). Mice were euthanized after 6 weeks because of the development of very large masses in the eyes of several mice in the control group. Eyes were enucleated and fixed in 4% paraformaldehyde and subjected to histological analysis.

Human Clinical Samples

Patients were diagnosed with UM by clinical history, complete ophthalmic examination, ultrasound, and ancillary studies. Twenty-three enucleated eyes due to large UM lesions were collected with patients’ consent and approval of the Institutional Review Board of West China Hospital. UM specimens were paraffin embedded and sectioned for histology and immunofluorescence staining. The use of human tissue samples was in accordance with the protocols approved by the Institutional Review Boards at West China Hospital and the University of California, San Diego.

Other methods are described in Supplemental Experimental Procedures.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Supplemental Experimental Procedures, three figures, and one table and can be found with this article online at http://dx.doi.org/10.1016/j.ccr.2014.04.017.

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