

A Single Residue Mutation in the $G\alpha_q$ Subunit of the G Protein Complex Causes Blindness in *Drosophila*

Jinguo Cao,* Murali K. Bollepalli,[†] Yuhui Hu,* Jin Zhang,* Qiang Li,[§] Hongmei Li,[§] Hua Chang,[§]

Feng Xiao,* Roger C. Hardie,[†] Yikang S. Rong,^{§,1} and Wen Hu^{§,1}

*Department of Medicine, Jinggang Shan University, Ji'an 343009, China, [†]Department of Physiology, Development and Neuroscience, University of Cambridge, CB2 3DY, United Kingdom, [‡]School of Basic Medical Sciences, Nanchang University, Jiangxi 330031, China, and [§]School of Life Sciences, Institute of Entomology, State Key Laboratory of Biocontrol, Sun Yat-sen University, Guangzhou 510006, China

ORCID ID: 0000-0002-9787-9669 (Y.S.R.)

ABSTRACT Heterotrimeric G proteins play central roles in many signaling pathways, including the phototransduction cascade in animals. However, the degree of involvement of the G protein subunit $G\alpha_q$ is not clear since animals with previously reported strong loss-of-function mutations remain responsive to light stimuli. We recovered a new allele of $G\alpha_q$ in *Drosophila* that abolishes light response in a conventional electroretinogram assay, and reduces sensitivity in whole-cell recordings of dissociated cells by at least five orders of magnitude. In addition, mutant eyes demonstrate a rapid rate of degeneration in the presence of light. Our new allele is likely the strongest hypomorph described to date. Interestingly, the mutant protein is produced in the eyes but carries a single amino acid change of a conserved hydrophobic residue that has been assigned to the interface of interaction between $G\alpha_q$ and its downstream effector, PLC. Our study has thus uncovered possibly the first point mutation that specifically affects this interaction *in vivo*.

KEYWORDS

phototransduction
photoreceptor
G protein
ERG
 $G\alpha_q$
 $G\alpha$ PLC interaction
light-induced
retinal
degeneration

G proteins are essential in the physiological responses to exogenous stimuli. G proteins normally consist of three subunits: $G\alpha$, $G\beta$, and $G\gamma$ (Neer 1995; Neves *et al.* 2002). In its inactive state, $G\alpha$ binds GDP and forms a heterotrimeric complex with $G\beta$ and $G\gamma$. Upon exogenous stimulation, GTP exchange factors, such as G protein-coupled receptors (GPCRs), convert $G\alpha$ into a GTP-bound state and release $G\alpha$ from $G\beta$ and $G\gamma$ (Siderovski and Willard 2005; Oldham and Hamm 2008; Rosenbaum *et al.* 2009; Campden *et al.* 2015). How $G\alpha$ activates downstream targets differs according to the types of $G\alpha$ involved. $G\alpha_s$ and $G\alpha_i$ both act through regulating the level of the secondary messenger cAMP, although in opposite ways (Hildebrandt *et al.* 1983; Sunahara

and Taussig 2002; Garcia-Marcos *et al.* 2009). The $G\alpha_q$ subfamily, on the other hand, acts by activating downstream phospholipase C (PLC) (Running Deer *et al.* 1995; Rhee 2001). Activated G protein heightens its GTPase activity by binding to GTPase-activating proteins (*e.g.*, RGS proteins or PLC itself) and converts the GTP-bound state into a GDP-bound one, thus terminating the biological response (Arshavsky and Bownds 1992; Cook *et al.* 2000; Ross and Wilkie 2000; Hollinger and Hepler 2002). Because G proteins are essential for a large number of biological processes and their dysfunction can lead to human diseases such as cancer, the mechanism by which G proteins function has been the subject of intense investigation (Zwaal *et al.* 1996; Ruppel *et al.* 2005; Kelly *et al.* 2006; Shan *et al.* 2006).

The visual system of the fruit fly *Drosophila* has been a fertile ground for studies of G protein. Upon light stimulation, the GPCR rhodopsin is transformed into its activated form, called metarhodopsin, which activates G protein (Lee *et al.* 1990, 1994; Kiselev and Subramaniam 1994; Scott *et al.* 1995). The activated $G\alpha_q$ subunit dissociates from $G\beta$ and $G\gamma$ and activates PLC, which in turn generates secondary messengers that ultimately open the TRP and TRPL Ca^{++} channels and results in the depolarization of the photoreceptor cells (Montell and Rubin 1989; Hardie and Minke 1992; Leung *et al.* 2008; Hardie and Franze 2012). Upon termination of the light stimulus, $G\alpha_q$ relocates to the cell membrane, reforms the heterotrimeric complex, and reverts to the inactive

Copyright © 2018 Cao *et al.*

doi: <https://doi.org/10.1534/g3.117.300340>

Manuscript received October 7, 2017; accepted for publication November 19, 2017; published Early Online November 20, 2017.

This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

¹Corresponding authors: School of Life Sciences, Institute of Entomology, State Key Laboratory of Biocontrol, Sun Yat-sen University, No.132, Outer Ring East Road, Guangzhou 510006, China. E-mail: rongyik@syls.edu.cn; and huwen6@mail.sysu.edu.cn

GDP-bound conformation. Many aspects of the light response in *Drosophila* can be reliably monitored by the simple electroretinogram (ERG) recording method (Wang *et al.* 2005a; Wang and Montell 2007), which has been widely used to identify mutants that are defective in various aspects of the phototransduction cascade.

Although placed in a central position in the phototransduction cascade, whether the $G\alpha_q$ subunit is essential for transduction has not been firmly established because existing mutants still have some response to light. This may reflect the hypomorphic nature of existing mutations or the fact that *Drosophila* $G\alpha_q$ has numerous splice variants, with different amino acid compositions and different tissue expression patterns (Lee *et al.* 1990; Talluri *et al.* 1995; Alvarez *et al.* 1996; Ratnaparkhi *et al.* 2002). For example, the original $G\alpha_q^1$ allele results in the loss of 99% of an eye-specific $G\alpha_q$ protein (quantified by Western blot analysis), yet still retains a substantial ERG response (Scott *et al.* 1995). Moreover, the $G\alpha_q^{961}$ allele with a premature stop codon in the head-specific isoform does not eliminate the ERG response (Hu *et al.* 2012). Moreover, neither mutation causes a rapid light-induced retinal degeneration, whereas other severe loss-of-function mutants of the visual system do.

In this study, we recovered a new $G\alpha_q$ allele with a single residue change in the most abundant isoform in the adult compound eye. Remarkably, this new allele has a much more severe phenotype than any previously identified $G\alpha_q$ alleles, yielding an essentially flat ERG response. The mutant eyes also demonstrate a rapid rate of light-induced degeneration. We show that the mutant $G\alpha_q$ protein is still expressed in the eye but is likely nonfunctional. Interestingly, the altered residue lies in a region of $G\alpha_q$ important for its interaction with PLC based on $G\alpha$ structural studies.

MATERIALS AND METHODS

Drosophila stocks

The genotype of wild-type flies used in our study is w^{1118} . All flies we used for this study were put into the w^{1118} background to eliminate the effects of genetic backgrounds. The collection from which our $G\alpha_q$ allele was recovered was kindly provided by Dr. Yi Rao's group at Beijing University of China. The mutant stocks of $G\alpha_q^1$, trp^{343} , and $norpA^{P24}$ were obtained from Dr. Junhai Han at Southeast University of China. The deficiency stocks and the *gmr-gal4* driver stock (BL8605) were from the Bloomington Stock Center. To avoid light and age-dependent retinal degeneration, flies were reared in standard medium at 25° in the dark and examined when they were 1–2 d old. The three mutations discussed in this study and their location according to Figure 1A of Alvarez *et al.* (1996) are: (1) $G\alpha_q^1$, which is a three amino acid deletion in exon 4A; (2) $G\alpha_q^{961}$, which is a premature stop in exon 4A; and (3) $G\alpha_q^{V303D}$, which is in exon 7A.

Rescuing $G\alpha_q$ phenotypes with transgenes

To generate transgenic flies carrying individual constructs of *UAS-G α_q* , *UAS-G α_q^{V303D}* , or *UAS-G α_q^{V303I}* , a wild-type cDNA clone of $G\alpha_q$ was changed to carry the V303D or V303I mutations using site-directed mutagenesis. All three cDNA clones were then subcloned into the pUAST-attB vector and introduced into *Drosophila* by phi-C31-mediated transformation. The transgenes were subsequently crossed into the $G\alpha_q^{V303D}$ mutant background and $G\alpha_q$ expression was driven by the eye-specific GMR-Gal4 driver.

Antibodies

Antibodies used in this study were mouse anti-TRP (83F6) (DSHB), mouse anti-Rh1 (4C5) (DSHB), rabbit anti- $G\alpha_q$ (Calbiochem), rabbit

anti-Arr2 (Han *et al.* 2006), rabbit anti-INAD (Wes *et al.* 1999), and anti-PLC (Wang *et al.* 2005b).

Electrophysiological recording

ERG recordings were performed as previously described (Hu *et al.* 2012). Briefly, 1 or 2-d-old flies were collected, immobilized with strips of tape, and kept in the dark for 5 min before recording. Two glass microelectrodes, filled with Ringer's solution, were placed on the compound eye and thorax. Flies were stimulated with a Newport light projector for a 5 sec light pulse (2000 Lux). The signal was amplified and recorded using a Warner IE210 Intracellular Electrometer. For each genotype, >10 flies were examined.

Whole-cell recordings

Whole-cell patch clamp recordings of photoreceptors of dissociated ommatidia from newly eclosed, dark-reared adult flies of either sex were performed as previously described (Hardie *et al.* 2004; Wang *et al.* 2005b). The bath contained (in mM) 120 NaCl, 5 KCl, 10 N-Tris-(hydroxymethyl)-methyl-2-amino-ethanesulfonic acid (TES), 4 MgCl₂, 1.5 CaCl₂, 25 proline, and 5 alanine (pH 7.15). The intracellular pipette solution (in mM) was 140 K gluconate, 10 TES, 4 Mg-ATP, 2 MgCl₂, 1 NAD, and 0.4 Na-GTP (pH 7.15).

Electron microscopy

Electron microscopy (EM) was performed as previously described (Hu *et al.* 2015). Briefly, fly heads were fixed for 2 hr in 0.5% glutaraldehyde, 4% paraformaldehyde, and 0.1 M sodium cacodylate (pH 7.2) at 4°. After three washes with 0.1 M sodium cacodylate, fly heads were stained with 1% osmium tetroxide for 1 hr at room temperature. They were washed three times and stained with uranyl acetate overnight. After a standard ethanol dehydration series, fly heads were rinsed in propylene oxide twice before they were embedded using standard procedures. Thin sections (100 nm) were cut at the top two thirds of retina, collected on Cu support grids, and stained with uranyl acetate for 15 min, followed with 10 min in lead citrate. Micrographs were taken at 120 kV on a JEM-1400 transmission EM.

Immunostaining

Section staining was carried out as previously described (Tian *et al.* 2013). Briefly, isolated fly heads were fixed for 2 hr at 4° with 4% paraformaldehyde in PBS. The fly heads were dehydrated with acetone and embedded in LR White resin. Cross-sections of 1 μ m were made across the top two thirds of retina, collected, and stained with antibodies (Rh1, 1:200; INAD, 1:400; TRP, 1:400). After being washed in PBS, cross-sections were incubated with secondary antibodies and Phalloidin at room temperature for 1 hr. The stained sections were examined under a ZEISS Axio Image A2 microscope.

$G\alpha_q$ protein translocation assay

$G\alpha_q$ translocation assay was performed as described previously (Frechter *et al.* 2007). Wild-type and mutant flies were each separated into three groups and treated differently. The D group (dark) was kept in the dark for 2 hr before they were killed for Western blotting. The L group (light) was kept in the dark for 2 hr, and then exposed to bright light for 2 hr before being killed. The LD group (light and dark) was kept in the dark for 2 hr, then exposed to bright light for 2 hr, and finally returned to complete darkness for 2 hr. Flies were snap-frozen in liquid nitrogen, and the heads isolated and homogenized in PBS. Pellets and supernatant fractions were separated by centrifuging at 14,000 \times g for 4 min before subjecting to Western blot analysis.

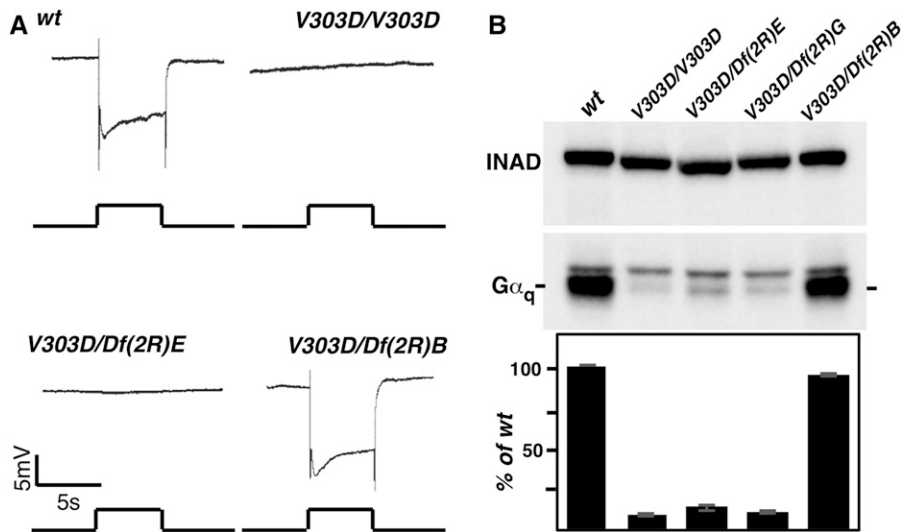


Figure 1 A new $G\alpha_q$ mutant with a flat ERG response. (A) ERG recording in various genetic backgrounds. Flies that are either homozygous for the V303D mutation or trans-heterozygous for V303D and a chromosomal deficiency uncovering the $G\alpha_q$ region “Df(2R)E” (abbreviated for Df(2R)Exel7121) show a nearly complete loss of response to light stimulation. However, flies trans-heterozygous for V303D and a chromosomal deficiency uncovering an adjacent region to $G\alpha_q$ “Df(2R)B” (abbreviated for Df(2R)BSC485) displayed a normal ERG recording. For all ERG recordings, event markers represent 5-sec orange light pulses, and scale bar for the vertical axis is 5 mV. (B) The level of $G\alpha_q$ protein in various genetic backgrounds. Western blot was used to detect $G\alpha_q$ protein level in whole exact from fly heads with the indicated genotypes. “Df(2R)G” is the abbreviation for Df(2R) $G\alpha_q$ 1.3. In each genotype, the $G\alpha_q$ band is marked and the

upper band is nonspecific. INAD was used as a loading control. Quantification of the Western blot results is shown below. The complete genotypes are as follows: w^{1118} (wt); $w^{1118}; G\alpha_q^{V303D}$ (V303D); $w^{1118}; G\alpha_q^{V303D}/Df(2R)Exel7121$ (V303D/Df(2R)E); $w^{1118}; G\alpha_q^{V303D}/Df(2R)G\alpha_q1.3$ (V303D/Df(2R)G); $w^{1118}; G\alpha_q^{V303D}/Df(2R)BSC485$ (V303D/Df(2R)B).

Data availability

The research reagents generated in this study are freely available upon request. The authors affirm that all data necessary for confirming the conclusions presented in the article are represented fully within the article.

RESULTS

A new $G\alpha_q$ allele with a flat ERG response

We have been using the ERG recording method to screen mutagenized *Drosophila* collections to uncover new players in the phototransduction

cascade. We recovered a new mutant line with a flat ERG response (Figure 1A and Figure 2A). Genetic mapping based on the loss of a ERG response revealed that the new mutation is uncovered by the chromosomal deficiencies of Df(2R)Exel7121 and Df(2R) $G\alpha_q$ 1.3, which include the *Drosophila* $G\alpha_q$ locus. Genomic sequencing identified a single T to A nucleotide change in $G\alpha_q$, making it the prime candidate for the responsible gene. This mutation results in a Val to Asp change at residue 303, and the mutant was thus named $G\alpha_q^{V303D}$, or V303D for short. The V303 residue is specific to the $G\alpha_q$ isoform in the eye.

To confirm that the V303D mutation is responsible for the flat ERG response, we introduced a wild-type copy of the $G\alpha_q$ cDNA driven by

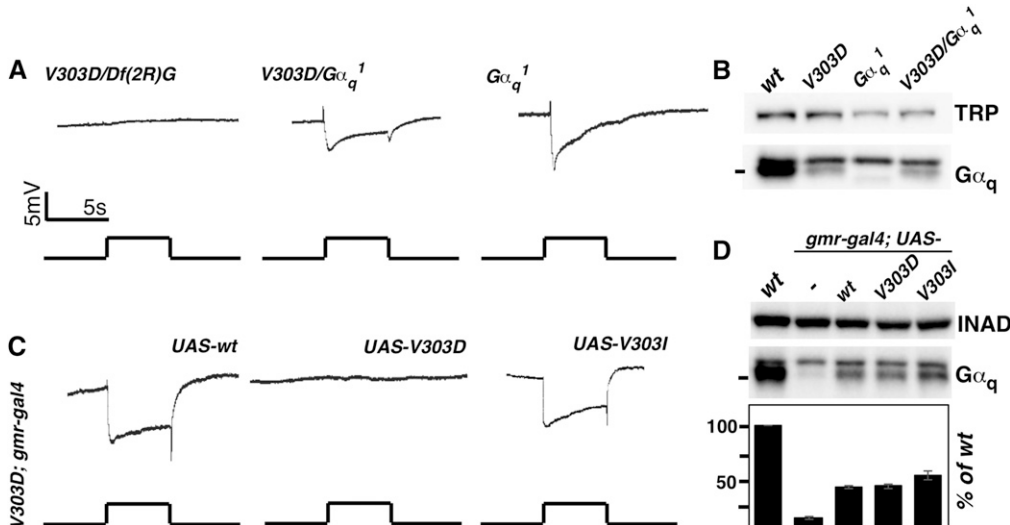


Figure 2 Defective $G\alpha_q$ protein but not the reduction in $G\alpha_q$ level is responsible for the loss of a light response. (A) ERG recordings of $G\alpha_q$ mutants. Flies trans-heterozygous for V303D and the deficiency Df(2R) $G\alpha_q$ 1.3 displayed no light response. Mutants either homozygous for the $G\alpha_q^1$ mutation or trans-heterozygous for $G\alpha_q^1$ and V303D displayed a substantial response to light. (B) Western blot analyses of $G\alpha_q$ protein level showed that $G\alpha_q$ level is lower in $G\alpha_q^1$ mutants than in V303D homozygous mutants. TRP serves as a loading control. (C) The ERG recordings of V303D mutants expressing different $G\alpha_q$ variants. Flies carrying homozygous V303D mutation, a GMR-Gal4 transgene, and different

ent UAS- $G\alpha_q$ transgenes were subject to ERG recording. Both the wild-type $G\alpha_q$ and the mammalian mimic V303I transgenes rescued the ERG phenotype. For all ERG traces, event markers represent 5-sec orange light pulses, and scale bars are 5 mV. (D) Western blot measurement of $G\alpha_q$ protein level in rescued lines. $G\alpha_q$ level was restored to 40% of the wild-type level when GMR-Gal4 was used to drive $G\alpha_q$ expression. INAD served as a loading control. Quantification of the Western blot results is given below. The complete genotypes are as follows: w^{1118} (wt); $w^{1118}; G\alpha_q^{V303D}$ (V303D); $w^{1118}; G\alpha_q^{V303D}/Df(2R)G\alpha_q1.3$ (V303D/Df(2R)G); $w^{1118}; G\alpha_q^1$ ($G\alpha_q^1$); $w^{1118}; G\alpha_q^{V303D}/G\alpha_q^1$ (V303D/ $G\alpha_q^1$); $w^{1118}; G\alpha_q^{V303D} gmr-Gal4$; UAS- $G\alpha_q^+$; $w^{1118}; G\alpha_q^{V303D} gmr-Gal4$; UAS- $G\alpha_q^{V303D}$; $w^{1118}; G\alpha_q^{V303D} gmr-Gal4$; UAS- $G\alpha_q^{V303I}$.

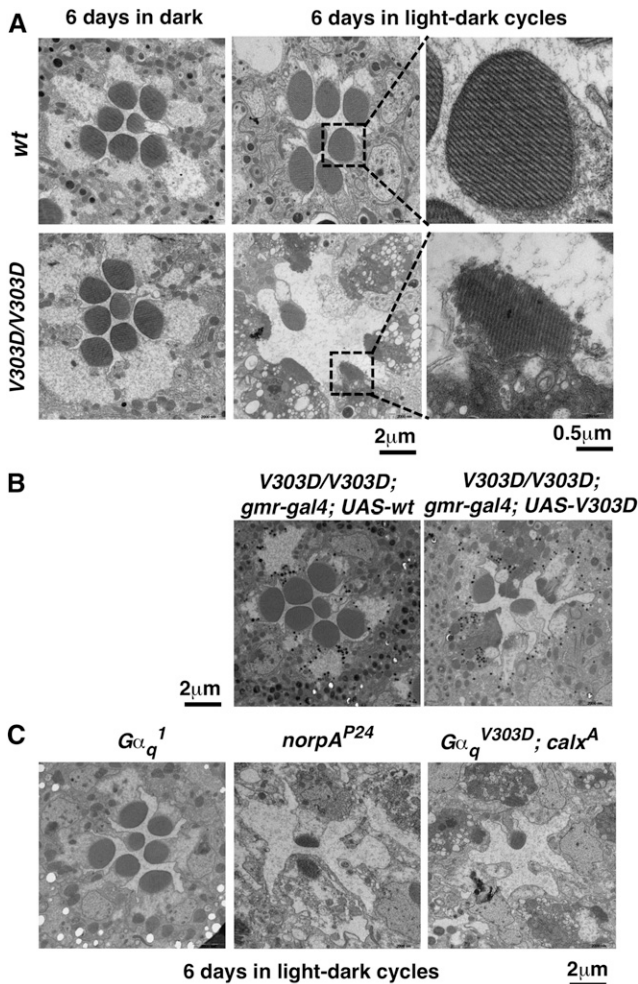


Figure 3 $G\alpha_q^{V303D}$ mutants undergo rapid light-dependent retinal degeneration. (A) Electron microscopy images of an ommatidium from wild-type and $V303D$ mutant eyes, with higher magnification images of selected rhabdomeres (highlighted with a square) shown to the right. Flies were raised for 6 d under either constant dark condition or a 12 hr light/12 hr dark cycle. (B) The GMR-driven wild-type $G\alpha_q$ transgene, but not the $V303D$ mutant transgene, rescues visual degeneration of the $V303D$ mutant. Scale bars are indicated at the bottom. (C) Retinal degeneration did not happen in similarly dark/light-treated 6-d-old eyes from $G\alpha_q^1$. Fast degeneration of $V303D$ eyes is similar to $norpA$ mutants, and could not be relieved by a $calx$ mutation. The complete genotypes are as follows: w^{1118} (wt); $w^{1118}; G\alpha_q^{V303D}$ ($V303D$); $w^{1118}; G\alpha_q^{V303D} gmr-Gal4; UAS-G\alpha_q^+$; $w^{1118}; G\alpha_q^{V303D} gmr-Gal4; UAS-G\alpha_q^{V303D}$; $w^{1118}; G\alpha_q^1; w^{1118}; norpA^{P24}$; $w^{1118}; G\alpha_q^{V303D}; calx^A$.

the eye-specific GMR promoter into $V303D$ homozygotes, or $V303D$ *trans*-heterozygotes with a $G\alpha_q$ deficiency, and was able to rescue the ERG response in both cases (Figure 2C). Therefore, the defective ERG response in our mutant is caused by a defective $G\alpha_q$ gene. It is worth noting that before our work, only a few genetic backgrounds were shown to produce a flat ERG response: single mutations in the *rdgA* gene that encodes diacylglycerol kinase (Masai *et al.* 1997; Raghu *et al.* 2000) and the *norpA* gene that encodes PLC (McKay *et al.* 1995; Kim *et al.* 2003), or double mutations in the *trp* and *trpl* channels (Leung *et al.* 2000, 2008; Yoon *et al.* 2000). This suggests that the new $G\alpha_q$ mutation that we identified is likely to be one of the strongest mutations of the phototransduction cascade in *Drosophila*.

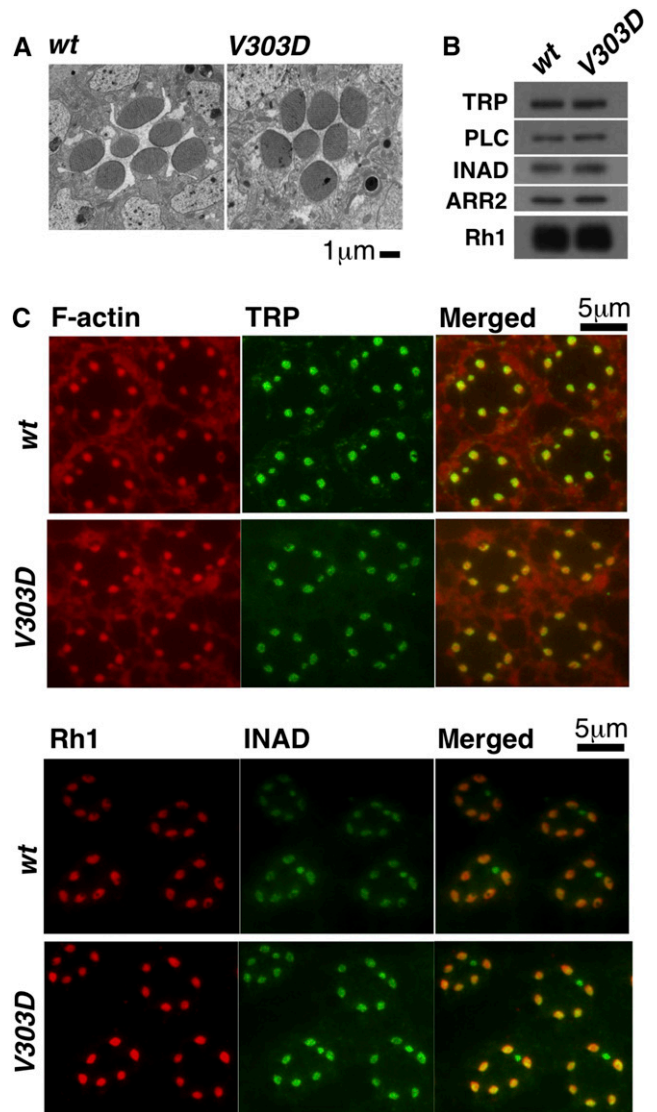


Figure 4 Normal rhabdomere structure and distribution of other visual factors in $G\alpha_q^{V303D}$ mutant. (A) EM images of 1-d-old wild-type and $G\alpha_q^{V303D}$ eyes showing normal rhabdomere structure. (B) Western blot results showing protein levels of phototransduction factors are similar between wild type and $V303D$ mutants that were 1 d old. (C) Immunostaining results showing normal distribution of phototransduction factors in $G\alpha_q^{V303D}$ mutant flies. The complete genotypes are as follows: w^{1118} (wt); $w^{1118}; G\alpha_q^{V303D}$ ($V303D$).

$G\alpha_q^{V303D}$ flies undergo rapid retinal degeneration

Many mutants in the *Drosophila* phototransduction cascade display light-dependent retinal degeneration, including flies with previously identified $G\alpha_q$ mutants (Hu *et al.* 2012). We raised $G\alpha_q^{V303D}$ adults under either regular light-dark cycles or constant dark conditions, and assayed retinal degeneration using EM. We observed severe degeneration in eyes taken from 6-d-old $G\alpha_q^{V303D}$ mutants raised under light-dark cycles (Figure 3A), but not from those reared in constant dark (Figure 3A). This degree of light-dependent retinal degeneration was more severe than in previously identified $G\alpha_q^1$ mutants (Figure 3B). Under similar rearing conditions, $G\alpha_q^1$ and $G\alpha_q^{961}$ mutant eyes display visible degeneration only after 21 d posteclosion (Hu *et al.* 2012). As shown in Figure 3B, this degree of fast degeneration in $V303D$ mutants

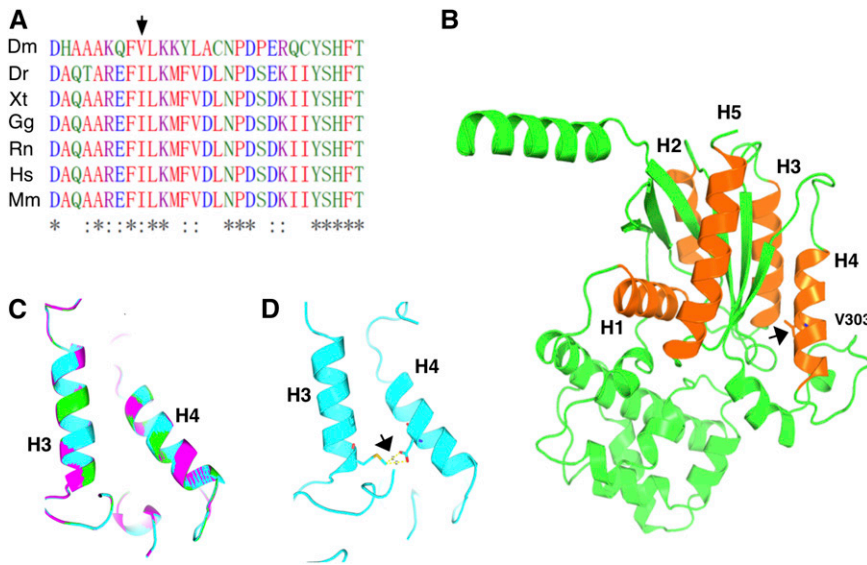


Figure 5 The molecular model of the V303D protein. (A) Alignment of the V303 region in $G\alpha_q$ proteins. The V303 residue is labeled with an arrow. (B) The structure of $G\alpha_q$ modeled over known $G\alpha$ structures, with the helices (H) involving in interaction with GPCR and PLC labeled in numbers. V303 is situated on helix 4, with its side chains shown and highlighted with an arrow. Helices 3 and 4 participate in interacting with PLC. (C) The predicted structures of helices 3 and 4 in wild type $G\alpha_q$ (green), $G\alpha_q^{V303I}$ (purple), and $G\alpha_q^{V303D}$ (cyan) proteins are overlaid to highlight a lack of major structural disruption of the V303D mutation. (D) In V303D, the side chain of the D303 mutant residue might participate in hydrogen bonding with M242 on helix 3 as indicated by the arrow. Dm, *Drosophila melanogaster*; Dr, *Danio rerio*; Gg, *Gallus gallus*; Hs, *Homo sapiens*; Mm, *Mus musculus*; Rn, *Rattus norvegicus*; Xt, *Xenopus tropicalis*.

resembles that in *norpA* mutants (loss of PLC), suggesting that the phototransduction pathway in the mutants might have terminated before reaching PLC. Importantly, this visual degeneration of $G\alpha_q^{V303D}$ eyes was rescued by the GMR-driven $G\alpha_q$ transgene (Figure 3B). Interestingly, increasing Ca^{++} concentration with the *calx^A* mutation was not able to rescue the degeneration phenotype (Figure 3C). Therefore, it is unlikely that a drop in Ca^{++} level in $G\alpha_q^{V303D}$ eyes leads to degeneration by preventing RdgC's dephosphorylation of M-PPP (Wang *et al.* 2005b).

$G\alpha_q^{V303D}$ encodes a nonfunctional protein

Both the $G\alpha_q^1$ and $G\alpha_q^{961}$ alleles previously identified behave as strong loss-of-function alleles (Figure 2A). However, the new $G\alpha_q^{V303D}$ allele lacks a response on a conventional ERG setting, although it does produce a small response with very bright illumination (see Figure 6). Interestingly, $G\alpha_q^{V303D}/G\alpha_q^1$ *trans*-heterozygotes behave similarly to

$G\alpha_q^1$ homozygous mutants (Figure 2A), consistent with $G\alpha_q^1$ being a hypomorphic mutation and V303D being a functionally null mutant based on ERG recordings. Since the $G\alpha_q^{961}$ mutant is no longer available, we were not able to test its genetic relationship with V303D.

Similar with other $G\alpha_q$ mutants, V303D results in a substantial reduction in protein level ($\sim 10\%$ of the wild-type level remaining) as shown by Western blot analyses of total proteins from adult heads (Figure 1B and Figure 2, B and D). However, it is unlikely that this reduction of $G\alpha_q$ protein alone could account for the essentially complete loss of visual capacity in V303D mutants, since $G\alpha_q^1$ results in a more severe loss of $G\alpha_q$ protein (Figure 2B) yet retains a substantial ERG response (Figure 2A). To provide direct evidence supporting the proposition that the visual defects in V303D are at least partly due to the production of a defective $G\alpha_q$ protein, we tested the effect of increasing the level of the V303D mutant protein. As shown in Figure 2D, GMR-driven expression of the wild-type $G\alpha_q$ protein, although only reaching

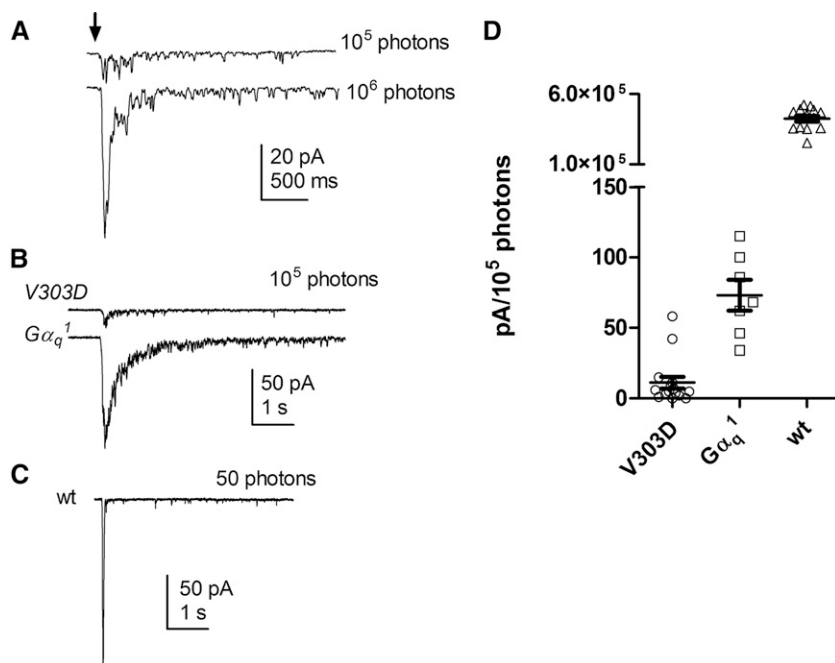


Figure 6 Light responses measured by whole-cell recording. (A) $G\alpha_q^{V303D}$ mutants display greatly reduced responses to 10 msec flashes containing $\sim 10^5$ and 10^6 effective photons. (B) $G\alpha_q^{V303D}$ mutant's response to 100 msec flashes containing 10^5 photons was greatly reduced when compared with that of $G\alpha_q^1$ mutants. (C) A wild-type response is shown. (D) Summary data of peak amplitudes in response to flashes containing 10^5 photons in wt ($n = 11$), $G\alpha_q^{V303D}$ ($n = 15$), and $G\alpha_q^1$ ($n = 7$) mutants. The complete genotypes are as follows: w^{1118} (wt); $w^{1118}; G\alpha_q^{V303D}$ (V303D); $w^{1118}; G\alpha_q^1$ ($G\alpha_q^1$).

~40% of the endogenous $G\alpha_q$ level in wild-type eyes, is sufficient to rescue the ERG defect in *V303D* mutants (Figure 2C). On the other hand, when the mutant *V303D* protein was expressed at a similar level (Figure 2D), it was still unable to rescue the ERG defect (Figure 2C). Therefore, a simple elevation of the $G\alpha_q^{V303D}$ protein is insufficient to restore visual function, implying that the *V303D* protein is itself defective, and that its nonfunctionality might have led to its instability.

Other components in the phototransduction cascade are normal in $G\alpha_q^{V303D}$ mutants

The flat ERG response of $G\alpha_q^{V303D}$ eyes resemble those produced by severe loss-of-function mutations of other components in the phototransduction cascade, such as those in the PLC enzyme (Harris and Stark 1977; McKay *et al.* 1995; Kim *et al.* 2003; LaLonde *et al.* 2005) and the TRP and TRPL channels downstream of the G protein (Leung *et al.* 2000, 2008; Yoon *et al.* 2000; Popescu *et al.* 2006). This suggests that the *V303D* mutant $G\alpha_q$ is unable to support phototransduction; however, we also considered the possibility that *V303D* is a neomorphic mutation and that the mutant protein indirectly affects the development of photoreceptor cells or the function of other components of the cascade.

We first ruled out that the *V303D* mutation is dominant or semi-dominant. When *V303D* was expressed in the wild-type background, using the *GMR* promoter, we did not observe any discernible visual defect. This was also the case when we raised the relative level of *V303D* protein further by lowering the wild-type dosage of $G\alpha_q$ with heterozygous $G\alpha_q$ deficiencies. In other words, eyes hemizygous for $G\alpha_q$ and expressing *gmr-V303D* are normal under our experimental conditions. Therefore, *V303D* is highly unlikely to be dominant to the wild-type allele.

To assess the integrity of other components of the cascade, we checked the structure of photoreceptor cells by EM, the localization of Rh1, TRP, and INAD proteins by immunostaining, and the level of Rh1, TRP, INAD, PLC, and ARR2 proteins by Western blot analysis. To eliminate the secondary effect of degenerated retinal structure suffered by older *V303D* eyes, our analyses were performed on samples taken from 1-d-old adults, when the overall eye structural remains normal (Figure 4A). As shown in Figure 4, B and C, neither the localization nor the expression level of the various protein components of the phototransduction cascade were altered by the *V303D* mutation. Therefore, the mutation affects $G\alpha_q$ specifically.

The *V303D* mutation might disrupt the interaction between $G\alpha_q$ and PLC

An alignment of the $G\alpha_q$ proteins from various organisms revealed that the *V303* residue lies in an important region of $G\alpha_q$ proteins (Figure 5A). Structural analyses of the $G\alpha$ proteins with regards to its interaction with PLC identified the *V303* region as the interface between the two proteins (Noel *et al.* 1993; Lambright *et al.* 1994, 1996; Alvarez *et al.* 1996). Interestingly, $G\alpha_q$ proteins in higher eukaryotes exhibit isoleucine at the position equivalent to the valine residue in the fly protein (Figure 5A), with both being hydrophobic. It is conceivable that the change of a hydrophobic residue to a polar one (D in the *V303D* mutant) can exert a large effect on the interaction between the two proteins. Consistent with this hypothesis, we were able to rescue the visual defects associated with *V303D* when we expressed a *V303I* variant of the fly protein (Figure 2C). We modeled the mutant protein using published structures of $G\alpha_q$ proteins. As shown in Figure 5C, neither the V to D nor the V to I change would lead to a dramatic change of the three-dimensional structure of $G\alpha_q$. The *V303* residue is situated in helix 4 of $G\alpha$ (Figure 5B). Interestingly, our structural model

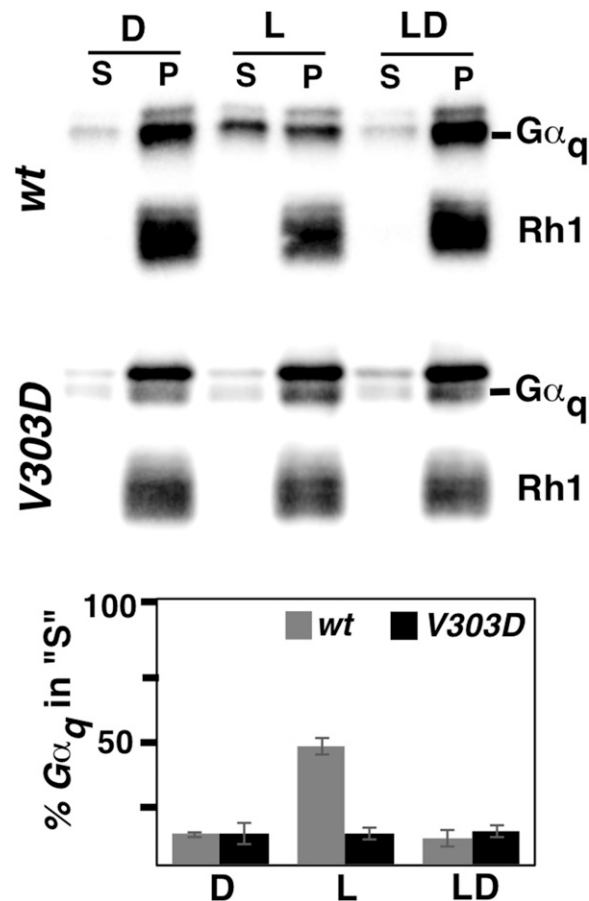


Figure 7 The $G\alpha_q^{V303D}$ protein is defective in cytoplasmic translocation induced by constant light stimulation. Wild-type and *V303D* mutant flies were each separated into three groups and treated differently (for treatment details see *Materials and Methods*). Supernatant (S) and membrane pellet (P) fractions of treated fly heads were subjected to Western blotting analyses, with Rh1 serving as a protein control for the membrane fraction (P). Quantification of the percentage of $G\alpha_q$ protein in the cytoplasm is shown below. The complete genotypes are as follows: w^{1118} (*wt*); $w^{1118}; G\alpha_q^{V303D}$ (*V303D*).

predicts that the side chains of a mutant Asp at position 303 would be in close proximity with Met at 242 in helix 3, another part of $G\alpha_q$ important for PLC interaction. The two residues might form hydrogen bonding, potentially affecting the $G\alpha_q$ -PLC interaction (Figure 5D).

Therefore, the defect of *V303D* could simply be that the mutant $G\alpha_q$ protein is unable to interact with and hence activate PLC. We attempted to use immunoprecipitation to investigate $G\alpha_q$ -PLC interaction. However, we were unable to detect association even under the wild-type condition. Nevertheless, the above hypothesis predicts that the lack of a photo response is simply due to the inability of the mutant protein to relay the signal, and that the downstream cascade should be functional in $G\alpha_q^{V303D}$ mutant. Our prior results showing normal expression level and localization of other components of the phototransduction cascade is consistent with this hypothesis (Figure 4).

To gain further evidence that the cascade was otherwise intact, we used whole-cell recording to investigate photoreceptor integrity and whether the function of the TRP channels is normal in the mutant eye. Consistent with our ultrastructural (EM) studies, dissociated ommatidia from *V303D* mutants appeared normal in appearance. Whole-cell recordings showed no sign of constitutive channel activity and cells had

capacitances (59.8 ± 2.2 pF; $n = 15$), similar to wild-type and essentially identical to that in $G\alpha_q^1$ mutant (58.4 ± 3.1 pF; $n = 8$), indicating that the area of microvillar membrane was unaffected. Interestingly, under whole-cell recording conditions, most $V303D$ mutant photoreceptors did display a slight response to very bright light stimuli, but with an ~ 10 -fold reduced sensitivity compared with the $G\alpha_q^1$ mutant (Figure 6). The kinetics and channel noise of these residual response were similar to those in $G\alpha_q^1$, suggesting that downstream components (PLC and TRP/TRPL channels) were functioning normally. Whether these responses were due to minimal residual function of the $V303D$ mutant or an alternative G protein isoform is unclear.

Impaired long-term adaptation in the $V303D$ mutant

In addition to responding to light stimuli, *Drosophila* eyes have the ability to adapt to maintained illumination. $G\alpha_q$ also participates in this long-term adaptation by shuttling between the cell membrane and the cytoplasm (Cronin *et al.* 2004; Frechter and Minke 2006). Under normal conditions, constant light stimulation results in the relocation of $G\alpha_q$ to the cytoplasm, to prevent overactivation of the visual system (Kosloff *et al.* 2003). Upon termination of light stimulation, $G\alpha_q$ returns to the membrane (Frechter *et al.* 2007). As shown in Figure 7, we were able to recapitulate this shuttling in wild-type eyes exposed to 2 hr of light stimulation. On the other hand, the $V303D$ mutant protein was unable to relocate to the cytoplasm upon a similarly long exposure to light, suggesting that the $G\alpha_q^{V303D}$ mutant is defective in long-term adaptation. However, we cannot rule out that the inability of the mutant protein to relocate is due to the lack of a photo response (*i.e.*, the light response is epistatic to the adaptation), even though we showed that the Rh1 receptor appears expressed and localized normally in the mutant (Figure 4).

DISCUSSION

In this study, we characterized a novel allele of the *Drosophila* $G\alpha_q$ gene. The mutant protein produced by this new allele possesses a single amino acid change from the wild-type version of an eye-specific isoform, yet it produces the strongest visual defects of all known $G\alpha_q$ mutants.

We suggest that the $G\alpha_q^{V303D}$ protein might have only affected the visual pathway at the level of the $G\alpha_q$ -PLC interaction. By Western blot and immunostaining analyses, we showed that key components of the phototransduction pathway are normal both at the protein level and at the subcellular localization level. In addition, the functional integrity of the remaining pathway is indicated by the normal kinetics of the residual light response in whole-cell recordings from mutant photoreceptors.

Structural studies suggest that the Val residue, which is mutated to Asp in our mutant, constitutes part of the interaction interface between $G\alpha$ and its downstream effector. Interestingly, Val is replaced with Ile in $G\alpha_q$ proteins from vertebrates, yet the hydrophobicity at this position is evolutionally conserved. Val and Ile appear interchangeable for *Drosophila* visual transduction, as the $G\alpha_q^{V303I}$ variant is functional under the conditions of our assays (Figure 2C). Therefore, it is highly likely that the change to a polar residue in $V303D$ causes a major disruption of the interaction between $G\alpha_q$ and its downstream effector, which in the case of *Drosophila* visual transduction is the PLC enzyme. The model that $V303D$ loses its ability to activate PLC predicts that $G\alpha_q^{V303D}$ would behave similarly to a *norpa* mutant with regard to the visual phenotypes. This is supported by existing data. First, *norpa* is one of very few mutants that produce a flat ERG response similarly to our $G\alpha_q$ mutant. Second, the $V303D$ mutant phenocopies a *norpa*

mutant in having the fastest rate of retinal degeneration induced by light.

Nevertheless, $G\alpha_q^{V303D}$ behaves differently from a *norpa* mutant in one aspect. $G\alpha_q^{V303D}$ protein is defective in relocation to the membrane during prolonged exposure to lights, whereas $G\alpha_q$ proteins in a *norpa* mutant behave normally (Kosloff *et al.* 2003; Cronin *et al.* 2004). Because the absence of PLC does not affect $G\alpha_q$'s relocation behavior, the molecular defect in $G\alpha_q^{V303D}$ must also prevent its translocation to the cytoplasm upon constant light exposure. As shown by others (Kosloff *et al.* 2003; Cronin *et al.* 2004), this dynamic relocation to the cytoplasm appears to be affected only by the state of Rh1. Importantly, none of the downstream components of the signaling pathway is important to regulate the membrane-to-cytoplasm dynamics of $G\alpha_q$, although the NinaC myosin III has a role in promoting the cytoplasm-to-membrane movement of $G\alpha_q$ (Cronin *et al.* 2004). This would appear to imply that the $G\alpha_q^{V303D}$ is also defective in its functional interaction with Rh1. However, our structural modeling suggests that this is unlikely to be the case. As shown in Figure 5, the $V303D$ change might not have altered the overall structure of $G\alpha_q$ including the regions important for GPCR interaction: helices 1 and 5. Therefore, the $V303D$ mutant protein might be intrinsically defective in this membrane to cytoplasm shuttling. Further work is required to distinguish these possibilities.

In summary, we have recovered a new point mutation of the important $G\alpha_q$ protein that essentially abolishes the visual transduction pathway in *Drosophila*. It also leads to one of the fastest rates of retinal degeneration induced by light. Although the molecular lesion lies in the interaction interface between $G\alpha_q$ and its effector, functional characterization suggests that the mutant protein might harbor additional molecular defects. Therefore, our work reveals additional complexity in the regulation of G protein functions and generates a potential useful reagent for fine structural and functional studies of $G\alpha_q$ in diverse organisms.

ACKNOWLEDGMENTS

We thank Junhai Han of Southeast University, China, in whose laboratory this work was initiated. We thank members of the Rong and Hardie laboratories for technical assistance and comments on the manuscript. This work was supported by the Science and Technology Program of Guangzhou, China (grant 201707010022 to W.H.), National Natural Science Foundation of China (grants 31660331 and 31460299 to J.C., 31601162 to W.H., and 31371364 to Y.S.R.), National Natural Science Foundation of Jiangxi province, China (grant 20151BAB214012 to J.C.), and Scientific Research Fund of Jiangxi Province Education Department (grant GJJ160728 to Y.H.). R.C.H. and M.K.B. are supported by a grant from the Biotechnology and Biological Sciences Research Council (BBSRC grant BB/M007006/1).

LITERATURE CITED

- Alvarez, C. E., K. Robison, and W. Gilbert, 1996 Novel Gq alpha isoform is a candidate transducer of rhodopsin signaling in a *Drosophila* testes-autonomous pacemaker. *Proc. Natl. Acad. Sci. USA* 93: 12278–12282.
- Arshavsky, V., and M. D. Bownes, 1992 Regulation of deactivation of photoreceptor G protein by its target enzyme and cGMP. *Nature* 357: 416–417.
- Campden, R., N. Audet, and T. E. Hebert, 2015 Nuclear G protein signaling: new tricks for old dogs. *J. Cardiovasc. Pharmacol.* 65: 110–122.
- Cook, B., M. Bar-Yaacov, H. Cohen Ben-Ami, R. E. Goldstein, Z. Paroush *et al.*, 2000 Phospholipase C and termination of G-protein-mediated signalling *in vivo*. *Nat. Cell Biol.* 2: 296–301.
- Cronin, M. A., F. Diao, and S. Tsunoda, 2004 Light-dependent subcellular translocation of $G_q\alpha$ in *Drosophila* photoreceptors is facilitated by the photoreceptor-specific myosin III NINAC. *J. Cell Sci.* 117: 4797–4806.

- Frechter, S., and B. Minke, 2006 Light-regulated translocation of signaling proteins in *Drosophila* photoreceptors. *J. Physiol. Paris* 99: 133–139.
- Frechter, S., N. Elia, V. Tzarfaty, Z. Selinger, and B. Minke, 2007 Translocation of G_qα mediates long-term adaptation in *Drosophila* photoreceptors. *J. Neurosci.* 27: 5571–5583.
- Garcia-Marcos, M., P. Ghosh, and M. G. Farquhar, 2009 GIV is a non-receptor GEF for Gαi with a unique motif that regulates Akt signaling. *Proc. Natl. Acad. Sci. USA* 106: 3178–3183.
- Han, J., P. Gong, K. Reddig, M. Mitra, P. Guo *et al.*, 2006 The fly CAMTA transcription factor potentiates deactivation of rhodopsin, a G protein-coupled light receptor. *Cell* 127: 847–858.
- Hardie, R. C., and K. Franze, 2012 Photomechanical responses in *Drosophila* photoreceptors. *Science* 338: 260–263.
- Hardie, R. C., and B. Minke, 1992 The *trp* gene is essential for a light-activated Ca²⁺ channel in *Drosophila* photoreceptors. *Neuron* 8: 643–651.
- Hardie, R. C., Y. Gu, F. Martin, S. T. Sweeney, and P. Raghu, 2004 *In vivo* light-induced and basal phospholipase C activity in *Drosophila* photoreceptors measured with genetically targeted phosphatidylinositol 4,5-bisphosphate-sensitive ion channels (Kir2.1). *J. Biol. Chem.* 279: 47773–47782.
- Harris, W. A., and W. S. Stark, 1977 Hereditary retinal degeneration in *Drosophila melanogaster*. A mutant defect associated with the phototransduction process. *J. Gen. Physiol.* 69: 261–291.
- Hildebrandt, J. D., R. D. Sekura, J. Codina, R. Iyengar, C. R. Manclark *et al.*, 1983 Stimulation and inhibition of adenyl cyclases mediated by distinct regulatory proteins. *Nature* 302: 706–709.
- Hollinger, S., and J. R. Hepler, 2002 Cellular regulation of RGS proteins: modulators and integrators of G protein signaling. *Pharmacol. Rev.* 54: 527–559.
- Hu, W., D. Wan, X. Yu, J. Cao, P. Guo *et al.*, 2012 Protein Gq modulates termination of phototransduction and prevents retinal degeneration. *J. Biol. Chem.* 287: 13911–13918.
- Hu, W., T. Wang, X. Wang, and J. Han, 2015 Ih channels control feedback regulation from amacrine cells to photoreceptors. *PLoS Biol.* 13: e1002115.
- Kelly, P., L. N. Stemmler, J. F. Madden, T. A. Fields, Y. Daaka *et al.*, 2006 A role for the G12 family of heterotrimeric G proteins in prostate cancer invasion. *J. Biol. Chem.* 281: 26483–26490.
- Kim, S., D. M. Chen, K. Zavarella, C. F. Fournier, W. S. Stark *et al.*, 2003 Substitution of a non-retinal phospholipase C in *Drosophila* phototransduction. *Insect Mol. Biol.* 12: 147–153.
- Kiselev, A., and S. Subramaniam, 1994 Activation and regeneration of rhodopsin in the insect visual cycle. *Science* 266: 1369–1373.
- Kosloff, M., N. Elia, T. Joel-Almagor, R. Timberg, T. D. Zars *et al.*, 2003 Regulation of light-dependent Gqα translocation and morphological changes in fly photoreceptors. *EMBO J.* 22: 459–468.
- LaLonde, M. M., H. Janssens, E. Rosenbaum, S. Y. Choi, J. P. Gergen *et al.*, 2005 Regulation of phototransduction responsiveness and retinal degeneration by a phospholipase D-generated signaling lipid. *J. Cell Biol.* 169: 471–479.
- Lambright, D. G., J. P. Noel, H. E. Hamm, and P. B. Sigler, 1994 Structural determinants for activation of the alpha-subunit of a heterotrimeric G protein. *Nature* 369: 621–628.
- Lambright, D. G., J. Sondek, A. Bohm, N. P. Skiba, H. E. Hamm *et al.*, 1996 The 2.0 Å crystal structure of a heterotrimeric G protein. *Nature* 379: 311–319.
- Lee, Y. J., M. B. Dobbs, M. L. Verardi, and D. R. Hyde, 1990 *dgg*: a *Drosophila* gene encoding a visual system-specific G alpha molecule. *Neuron* 5: 889–898.
- Lee, Y. J., S. Shah, E. Suzuki, T. Zars, P. M. O'Day *et al.*, 1994 The *Drosophila* *dgg* gene encodes a G_α protein that mediates phototransduction. *Neuron* 13: 1143–1157.
- Leung, H. T., C. Geng, and W. L. Pak, 2000 Phenotypes of *trpl* mutants and interactions between the transient receptor potential (TRP) and TRP-like channels in *Drosophila*. *J. Neurosci.* 20: 6797–6803.
- Leung, H. T., J. Tseng-Crank, E. Kim, C. Mahapatra, S. Shino *et al.*, 2008 DAG lipase activity is necessary for TRP channel regulation in *Drosophila* photoreceptors. *Neuron* 58: 884–896.
- Masai, I., E. Suzuki, C. S. Yoon, A. Kohyama, and Y. Hotta, 1997 Immunolocalization of *Drosophila* eye-specific diacylglycerol kinase, *rdgA*, which is essential for the maintenance of the photoreceptor. *J. Neurobiol.* 32: 695–706.
- McKay, R. R., D. M. Chen, K. Miller, S. Kim, W. S. Stark *et al.*, 1995 Phospholipase C rescues visual defect in *norPA* mutant of *Drosophila melanogaster*. *J. Biol. Chem.* 270: 13271–13276.
- Montell, C., and G. M. Rubin, 1989 Molecular characterization of the *Drosophila* *trp* locus: a putative integral membrane protein required for phototransduction. *Neuron* 2: 1313–1323.
- Neer, E. J., 1995 Heterotrimeric G proteins: organizers of transmembrane signals. *Cell* 80: 249–257.
- Neves, S. R., P. T. Ram, and R. Iyengar, 2002 G protein pathways. *Science* 296: 1636–1639.
- Noel, J. P., H. E. Hamm, and P. B. Sigler, 1993 The 2.2 Å crystal structure of transducin-α complexed with GTP γS. *Nature* 366: 654–663.
- Oldham, W. M., and H. E. Hamm, 2008 Heterotrimeric G protein activation by G-protein-coupled receptors. *Nat. Rev. Mol. Cell Biol.* 9: 60–71.
- Popescu, D. C., A. J. Ham, and B. H. Shieh, 2006 Scaffolding protein INAD regulates deactivation of vision by promoting phosphorylation of transient receptor potential by eye protein kinase C in *Drosophila*. *J. Neurosci.* 26: 8570–8577.
- Raghu, P., K. Usher, S. Jonas, S. Chyb, A. Polyanovsky *et al.*, 2000 Constitutive activity of the light-sensitive channels TRP and TRPL in the *Drosophila* diacylglycerol kinase mutant, *rdgA*. *Neuron* 26: 169–179.
- Ratnaparkhi, A., S. Banerjee, and G. Hasan, 2002 Altered levels of Gq activity modulate axonal pathfinding in *Drosophila*. *J. Neurosci.* 22: 4499–4508.
- Rhee, S. G., 2001 Regulation of phosphoinositide-specific phospholipase C. *Annu. Rev. Biochem.* 70: 281–312.
- Rosenbaum, D. M., S. G. Rasmussen, and B. K. Kobilka, 2009 The structure and function of G-protein-coupled receptors. *Nature* 459: 356–363.
- Ross, E. M., and T. M. Wilkie, 2000 GTPase-activating proteins for heterotrimeric G proteins: regulators of G protein signaling (RGS) and RGS-like proteins. *Annu. Rev. Biochem.* 69: 795–827.
- Running Deer, J. L., J. B. Hurley, and S. L. Yarfitz, 1995 G protein control of *Drosophila* photoreceptor phospholipase C. *J. Biol. Chem.* 270: 12623–12628.
- Ruppel, K. M., D. Willison, H. Kataoka, A. Wang, Y. W. Zheng *et al.*, 2005 Essential role for Gα₁₃ in endothelial cells during embryonic development. *Proc. Natl. Acad. Sci. USA* 102: 8281–8286.
- Scott, K., A. Becker, Y. Sun, R. Hardy, and C. Zuker, 1995 G_qα protein function in vivo: genetic dissection of its role in photoreceptor cell physiology. *Neuron* 15: 919–927.
- Shan, D., L. Chen, D. Wang, Y. C. Tan, J. L. Gu *et al.*, 2006 The G protein Gα₁₃ is required for growth factor-induced cell migration. *Dev. Cell* 10: 707–718.
- Siderovski, D. P., and F. S. Willard, 2005 The GAPs, GEFs, and GDIs of heterotrimeric G-protein alpha subunits. *Int. J. Biol. Sci.* 1: 51–66.
- Sunahara, R. K., and R. Taussig, 2002 Isoforms of mammalian adenyl cyclase: multiplicities of signaling. *Mol. Interv.* 2: 168–184.
- Talluri, S., A. Bhatt, and D. P. Smith, 1995 Identification of a *Drosophila* G protein alpha subunit (dGq alpha-3) expressed in chemosensory cells and central neurons. *Proc. Natl. Acad. Sci. USA* 92: 11475–11479.
- Tian, Y., T. Li, M. Sun, D. Wan, Q. Li *et al.*, 2013 Neurexin regulates visual function via mediating retinoid transport to promote rhodopsin maturation. *Neuron* 77: 311–322.
- Wang, T., and C. Montell, 2007 Phototransduction and retinal degeneration in *Drosophila*. *Pflugers Arch.* 454: 821–847.

- Wang, T., Y. Jiao, and C. Montell, 2005a Dissecting independent channel and scaffolding roles of the *Drosophila* transient receptor potential channel. *J. Cell Biol.* 171: 685–694.
- Wang, T., H. Xu, J. Oberwinkler, Y. Gu, R. C. Hardie *et al.*, 2005b Light activation, adaptation, and cell survival functions of the Na⁺/Ca²⁺ exchanger CalX. *Neuron* 45: 367–378.
- Wes, P. D., X. Z. Xu, H. S. Li, F. Chien, S. K. Doberstein *et al.*, 1999 Termination of phototransduction requires binding of the NINAC myosin III and the PDZ protein INAD. *Nat. Neurosci.* 2: 447–453.
- Yoon, J., H. C. Ben-Ami, Y. S. Hong, S. Park, L. L. Strong *et al.*, 2000 Novel mechanism of massive photoreceptor degeneration caused by mutations in the *trp* gene of *Drosophila*. *J. Neurosci.* 20: 649–659.
- Zwaal, R. R., J. Ahringer, H. G. van Luenen, A. Rushforth, P. Anderson *et al.*, 1996 G proteins are required for spatial orientation of early cell cleavages in *C. elegans* embryos. *Cell* 86: 619–629.

Communicating editor: B. Reed