TOR-mediated autophagy regulates cell death in *Drosophila* neurodegenerative disease

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Target of rapamycin (TOR) signaling is a regulator of cell growth. TOR activity can also enhance cell death, and the TOR inhibitor rapamycin protects cells against proapoptotic stimuli. Autophagy, which can protect against cell death, is negatively regulated by TOR, and disruption of autophagy by mutation of Atg5 or Atg7 can lead to neurodegeneration. However, the implied functional connection between TOR signaling, autophagy, and cell death or degeneration has not been rigorously tested. Using the *Drosophila* melano-gaster visual system, we show in this study that hyperactivation of TOR leads to photoreceptor cell death in an age- and light-dependent manner and that this is because of TOR’s ability to suppress autophagy. We also find that genetically inhibiting TOR or inducing autophagy suppresses cell death in *Drosophila* models of Huntington’s disease and phospholipase C (norpA)-mediated retinal degeneration. Thus, our data indicate that TOR induces cell death by suppressing autophagy and provide direct genetic evidence that autophagy alleviates cell death in several common types of neurodegenerative disease.

Introduction

The evolutionarily conserved serine/threonine protein kinase target of rapamycin (TOR), a central effector of cell growth, controls diverse metabolic outputs, including protein translation, mRNA transcription, cytoskeletal organization, autophagy, and cell death (Wullschleger et al., 2006). Although most of the research on TOR has focused on its growth-promoting activity, hyperactive TOR signaling can also enhance the induction of cell death by various signals (Shah et al., 2004; Ghosh et al., 2006), and inhibition of TOR signaling can protect cells against proapoptotic insults (Ravikumar et al., 2006). The mechanisms underlying the relationship between TOR signaling and cell death are largely unknown, but the induction of autophagy that occurs when TOR activity is suppressed has been proposed to alleviate cellular toxicity in several neurodegenerative disease models (Rubinsztein et al., 2007; Mizushima et al., 2008).

Although unchecked autophagy can sometimes lead to cell death (Berry and Baehrecke, 2007; Scott et al., 2007), in vivo autophagy is mainly involved in eliminating damaged organelles or proteins with compromised function and can actually protect cells against death signals (Levine and Yuan, 2005; Klionsky, 2007). In fact, disruption of basal autophagy by loss of function of either Atg5 or Atg7, genes which are necessary for autophagosome formation, can lead to neurodegeneration in otherwise normal neurons (Hara et al., 2006; Komatsu et al., 2006, 2007).

The prosurvival function of autophagy might have a protective role against the development of several diseases, most notably neurodegenerative diseases involving formation of intracellular aggregates (Rubinsztein et al., 2007). Many pathogenic aggregate-prone proteins, including polyglutamine (polyQ)-expanded huntingtin are strongly dependent on autophagy for their degradation (Ravikumar et al., 2002; Berger et al., 2006; Shibata et al., 2006), and rapamycin attenuates accumulation of mutated huntingtin proteins and cell death in Huntington’s disease (HD) models (Ravikumar et al., 2004; Shibata et al., 2006). These findings have led to the proposition that autophagy induction might be used to treat neurodegenerative diseases such as HD (Ravikumar et al., 2002). However, it has not...
been genetically tested whether inhibition of TOR activity can suppress neuronal cell death in disease models or whether such suppression is autophagy dependent. Furthermore, it is not yet clear whether controlling TOR pathway activity and autophagy might suppress neurodegenerative diseases not associated with protein aggregation. Moreover, TOR activity, autophagy, and neurodegenerative cell death have not been functionally linked by genetic tests, although their association has been discussed (Ravikumar et al., 2004).

The Drosophila melanogaster visual system has proven to be a powerful genetic model for dissecting the molecular mechanisms underlying neurodegenerative diseases (Bilen and Bonini, 2005; Wang and Montell, 2007). Using the Drosophila visual system, we found that hyperactivation of TOR signaling led to neuronal cell death in an age- and light-dependent manner, and this was mediated via the suppression of autophagy. Either genetically inhibiting TOR or directly inducing autophagy also suppressed cell death in HD model. We further demonstrate that autophagy induction also greatly suppressed retinal degeneration associated with norpA mutations, possibly by mediating the turnover of toxic rhodopsin–arrestin complexes generated during phototransduction.

Results and discussion

TOR kinase is activated by the small GTPase Ras homologue enriched in brain protein (Rheb). The tuberous sclerosis complex (TSC) gene products Tsc1 and Tsc2 form a GTPase-activating protein that suppresses Rheb activity and thereby negatively regulates TOR kinase activity (Wullschleger et al., 2006). Therefore, to activate the TOR pathway, we overexpressed Rheb in Drosophila compound eyes using the Gal4/upstream activator sequence (UAS) system. Using the transgene combination UAS-rheb and glass multiple reporter (GMR)–Gal4 (an eye-specific Gal4 driver), we selectively overexpressed Rheb in photoreceptor neurons. The Drosophila compound eye consists of ~800 repetitive units, known as ommatidia, each of which includes seven photoreceptor cells in any given plane of a tangential section. Each photoreceptor cell contains a microvillar structure, the rhabdomere, which is the photoreception organelle and is centrally located in the ommatidium (Fig. 1 A, R). Control retinas (GMR-Gal4/+) had all seven photoreceptor cells in each ommatidium regardless of their age or whether or not they were maintained in the light or dark (Fig. 1, A and G). Young GMR-Gal4 UAS-rheb/+ (GMR>rheb) flies had normal eye morphology, although the ommatidium size was much larger than in controls (Fig. S1). However, GMR>rheb flies underwent an age-dependent loss of photoreceptor cells when cultured on a 12-h light/12-h dark cycle (Fig. 1, B, C, and G). Interestingly, GMR>rheb flies cultured in continuous darkness lost photoreceptor cells more slowly than those exposed to light (Fig. 1, D and G), indicating that photoreceptor degeneration in the Rheb-overexpressing eyes was dependent on phototransduction.

We also assayed photoreceptor cell death associated with mutation of tsc1, an essential negative regulator of Rheb. Using the ey-Gal4 UAS-FLP/hid system (Stowers and Schwarz, 1999), we generated eyes homozygous for a tsc1 loss of function allele. Whereas young tsc129 mosaic flies (<2 d old) had all seven rhabdomeres (Fig. 1 E), almost no rhabdomeres were present in the eyes of tsc129 mosaic flies after 20 d of light/dark cycling (Fig. 1, F and G). This is consistent with our observation that overexpressed Rheb led to photoreceptor cell degeneration.

TOR kinase controls cell growth in part via two well-characterized regulators of protein translation, the P70 ribosomal S6 kinase (S6K) and eukaryotic initiation factor 4E–binding protein (4EBP). Therefore, we considered the possibility that TOR might affect retinal degeneration by inducing cellular overgrowth, as promoted by S6k and 4EBP. Both GMR>rheb flies and tsc129 mosaic flies had hypertrophic eyes (Fig. S1). To reduce this hypertrophy, we used UAS-rheb/+;ninaE-Gal4/+ (ninaE>rheb) flies, which only expressed Rheb in adult R1–R6 photoreceptors. The eyes of ninaE>rheb flies were similar in size to controls (Fig. S1) and had normal retinal morphology when the flies were young (<2 d old; Fig. 2 A). However, few R1–R6 rhabdomeres were detected in light-exposed 30-d-old ninaE>rheb flies, although R7 rhabdomeres were generally present (Fig. 2, B and F). To further test the idea that cell overgrowth might be responsible for neuronal degeneration in the presence of excess TOR activity, we examined the ommatidial morphology of both GMR-Gal4/UAS-s6k29 (GMR>s6k) flies, which overexpress constitutively active S6K, and thor2 flies, which are mutant for 4EBP (Telemann et al., 2005). After 30 d of light/dark cycling, photoreceptors were preserved normally in both the GMR>s6k flies and the thor2 flies (Fig. 2, C, D, and F). This indicates that Rheb-induced photoreceptor cell death occurs independently of S6K and 4EBP and is most likely not a consequence of increased cell growth.

Because TOR drives negative feedback regulation of phosphatidylinositol 3 kinase (PI3K) signaling via S6K and IRS1 (Harrington et al., 2004; Shah et al., 2004), increases in TOR activity can decrease the activity of AKT, which is a universal survival signal (Datta et al., 1999). To test whether Rheb induced neuronal cell death through PI3K/AKT, we overexpressed PTEN (phosphatase and tensin homologue), a negative effector of PI3K signaling (Gao et al., 2000). No photoreceptor cell death was detected in 30-d-old GMR-Gal4/UAS-pten (GMR>pten) flies exposed to light (Fig. 2, E and F), suggesting that a reduction of PI3K/AKT activity is probably not responsible for Rheb-induced photoreceptor cell death.

In addition to growth signaling, TOR is important as a negative regulator of autophagy. To assess the possibility that TOR activation might cause neuronal degeneration by suppressing autophagy, we first tested whether a mutation in atg7 (Juhász et al., 2007), a gene required for autophagy, could induce photoreceptor cell loss. Whereas all seven rhabdomeres were typically detected in the ommatidia of young (<2 d old) atg7d77 flies, after 20 d of light/dark cycling, few rhabdomeres were detected (Fig. 3, A–D).

We reasoned that if retinal degeneration caused by hyperactive TOR is caused by the suppression of autophagy, the reactivation of autophagy might suppress cell death caused by excessive TOR activity. Because overexpression of Atg1 is sufficient to induce high levels of autophagy in Drosophila
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autophagy in the eye by overexpression of Atg1 did not suppress TOR activity. Compared with ninaE>rheb flies, which lost most major photoreceptor neurons after 30 d of light/dark culture, ninaE>rheb/ninaE-atg1 flies retained most of their photoreceptor cells (Fig. 3, E–H). Thus, these results show that enforced autophagy can suppress TOR-dependent neural degeneration, strongly supporting the idea that TOR-induced neuronal cell death is a consequence of the inhibition of autophagy.

(Scott et al., 2007), we generated transgenic flies expressing tagged Atg1 under the control of the ninaE promoter (ninaE-atg1). In ninaE-atg1 flies, high levels of Atg1-MYC protein were detected in the head, and autophagy, as assayed by LysoTracker staining, was strongly increased in photoreceptor cell bodies (Fig. S2). Although it has been hypothesized that autophagy can down-regulate TOR (Lee et al., 2007), we observed that S6K phosphorylation was not affected by the ninaE-atg1 transgene (Fig. S2), implying that induction of autophagy in the eye by overexpression of Atg1 did not suppress TOR activity. Compared with ninaE>rheb flies, which lost most major photoreceptor neurons after 30 d of light/dark culture, ninaE>rheb/ninaE-atg1 flies retained most of their photoreceptor cells (Fig. 3, E–H). Thus, these results show that enforced autophagy can suppress TOR-dependent neural degeneration, strongly supporting the idea that TOR-induced neuronal cell death is a consequence of the inhibition of autophagy.

Figure 1. Light-dependent photoreceptor degeneration in flies with overexpression of Rheb. (A–F) Examination of the morphology by transmission EM. Cross sections were obtained from 2 (D2) or 20-d-old (D20) flies maintained under 12-h light/12-h dark cycle, with the exception of the dark-reared GMR>rheb. 20-d-old control (GMR-Gal4/+; A), 2-d-old GMR>rheb (B), 20-d-old GMR>rheb (C), 20-d-old GMR>rheb reared in the dark (D), 2-d-old tsc129 (E), and 20-d-old tsc129 (F) are shown. (G) The time course of retinal degeneration, as determined by examining the number of rhabdomeres per ommatidium. Error bars indicate SD. R, rhabdomere. Bar, 2 µm.
It has been proposed that suppression of TOR activity and the induction of autophagy have protective roles toward many neurodegenerative diseases (Ravikumar et al., 2004). One such condition is HD, a devastating autosomal dominant neurodegenerative disease caused by polyQ-expanded huntingtin protein. In animal models of HD, the TOR inhibitor rapamycin can attenuate cell death (Ravikumar et al., 2004), and mutations in autophagy genes can enhance polyQ aggregation and neurodegeneration (Jia et al., 2007). However, whether the effects of TOR on polyQ-mediated neurodegeneration are caused by its regulation of autophagy has not been directly or genetically tested. On the contrary, one recent study using the *Drosophila* eye implicated S6K and PDK1 rather than autophagy as enhancers of polyQ-mediated neurodegeneration (Nelson et al., 2005). To explore the role of TOR-dependent autophagy in HD, we expressed N-terminal fragments of human huntingtin that contain 120 glutamine residues in photoreceptor neurons (Jackson et al., 1998). The GMR-hht.Q120 flies (HQ120) manifested strong age-dependent loss of rhabdomeres and photoreceptor nuclei in an optical neutralization assay and by EM (Fig. 4, A and B). Inhibition of TOR by overexpression of TSC1 and TSC2 (GMR>Tsc1/2) largely suppressed neural degeneration caused by HQ120 (Fig. 4, A–C). Furthermore, direct induction of autophagy by overexpressed ATG1 (ninaE-atg1) also suppressed photoreceptor cell death in the HQ120 flies (Fig. 4, A and D). These results support the idea that inducing autophagy by inhibiting TOR can suppress neurodegenerative diseases involving protein aggregates such as HD.

To further explore the mechanisms underlying TOR’s neuroprotective function, we used two well-known genetic models of retinal degeneration. *NinaE<sup>RH27</sup>* encodes a dominant mutant in the major rhodopsin Rh1, which promotes retinal cell death through apoptosis (Davidson and Steller, 1998). *NinaE<sup>RH27</sup>* flies started to lose photoreceptor cells after 25 d of 12-h light/12-h dark cycling (Fig. S3, A and D). Overexpression of TSC1 and TSC2 (GMR>Tsc1/2) did not attenuate cell death in the *NinaE<sup>RH27</sup>* flies and even had converse effects (Fig. S3, B and E). Moreover, direct induction of autophagy by overexpression of Atg1 did not suppress cell death caused by the dominant *NinaE<sup>RH27</sup>* mutation (Fig. S3, C and F). Thus, the suppression of TOR activity or the induction of autophagy cannot protect cells from all kinds of cell death. In this case, caspase-dependent apoptosis appeared to be TOR independent.

In a second neurodegeneration model, mutations in the *Drosophila* phospholipase C gene norpA result in light-dependent retinal degeneration triggered by the accumulation of cytosolic
rhodopsin–arrestin complexes (Alloway et al., 2000). Neuronal degeneration in the norpA model cannot be suppressed by the inhibitors of apoptosis and thus seems not to be mediated by apoptosis (Hsu et al., 2004). We found that norpA<sup>P24</sup> mutants underwent rapid retinal degeneration, such that the animals had detectable loss of photoreceptors cells by 4 d and were almost devoid of photoreceptor cells by day 10 (Fig. 5, A and B). The norpA-mediated degeneration was significantly suppressed by overexpression of either TSC1 and TSC2 or Atg1 in photoreceptor cells (Fig. 5, A, C, and D). Thus, the suppression of autophagy by TOR activity is a critical component in norpA-mediated neurodegeneration.

Stable rhodopsin–arrestin complexes are known to trigger the cell death that occurs in the norpA mutants (Alloway et al., 2000), and therefore, we considered whether autophagy might suppress norpA-mediated cell death by clearing these toxic complexes. To test this, we assayed the percentage of major arrestin (Arr2) bound to rhodopsin using a coprecipitation assay. We found that exposure to light for 1 h caused ~45% of the Arr2 to bind to rhodopsin in wild-type eyes, whereas >60% was bound in norpA mutants (Fig. 5, E and F). However, in both norpA<sup>P24</sup>;ninaE-atg1 and norpA<sup>P24</sup>;GMR>Tsc1/2 flies, the fraction of rhodopsin-bound Arr2 was decreased back nearly to the wild-type level without changing the overall rhodopsin/Arr2 ratio (Fig. 5, E and F). These data illustrate that autophagy can help eliminate rhodopsin–arrestin complexes and thus reduce their toxicity in the norpA model of retinal degeneration.

Overall, our results indicate that constraining TOR activity is crucial for neuronal survival, especially in highly active neurons, and that this is caused by, in large part, TOR’s function as a suppressor of autophagy. Importantly, we found that the direct induction of autophagy by overexpression of Atg1 largely suppressed Rheb-induced photoreceptor cell death as well as photoreceptor neural degeneration in Drosophila models of HD and phospholipase C deletion. Our results support the idea that the continuous clearance of cytosolic components through autophagy is important for preventing the accumulation of toxic proteins that would otherwise disrupt neural function and ultimately lead to neurodegeneration.

Autophagy has been shown to be important in the clearance of cellular aggregates in several neurodegenerative disease models (Ravikumar et al., 2002; Webb et al., 2003; Iwata et al., 2005). Moreover, recent studies have suggested that the TOR inhibitor rapamycin can attenuate cell death in several intracytosolic proteinopathies and that this might occur through the up-regulation of autophagy (Ravikumar et al., 2004; Berger et al., 2006). Thus, our genetic demonstration that suppression of TOR or activation of autophagy can cell-autonomously suppress neurodegeneration in a polyQ aggregation model provides direct genetic evidence to support this prevailing view of neurodegenerative diseases. Interestingly, heat shock proteins such as Hsp70 and Hsp40, which function as chaperones to prevent protein aggregation, as well as several components of the ubiquitin proteasome can suppress polyQ-induced degeneration (Warrick et al., 1999; Fernandez-Funez et al., 2000; Kazemi-Esfarjani and Benzer, 2000). Like autophagy, both pathways have key roles in protein quality control, emphasizing the significant

Figure 3. Rheb/TOR signaling drives photoreceptor cell death by suppressing autophagy. (A–C) Transmission EM images of cross sections from wild type (w<sup>1118</sup>; A), atg<sup>707</sup> (B), and atg<sup>707</sup> dark reared (C). The sections were obtained from 30-d-old flies maintained under 12-h light/12-h dark cycle, with the exception of dark-reared atg<sup>707</sup> (C). (D) Histogram of the mean number of rhabdomeres per ommatidium from 30-d-old flies. (E–G) Retinal morphology of ninaE>rheb (E), ninaE-atg1 (F), and ninaE>rheb/ninaE-atg1 (G). The sections were obtained from 30-d-old flies maintained under 12-h light/12-h dark cycle. (H) Histogram of the mean number of rhabdomeres per ommatidium from 30-d-old flies. (D and H) Error bars indicate SD. Bar, 2 µm.
that arise via unchecked cell growth are commonly believed to be the principal adverse effect in TSC disease, cell death has been detected inside these tumors (Maldonado et al., 2003; Zeng et al., 2007). Thus, an alternative explanation for some of the symptoms of TSC such as seizures is that they arise as a consequence of neural cell death and neurodegeneration.

Materials and methods

Drosophila stocks

ninaE-Gal4, GMR-Gal4, and GMR-Gal4 flies were obtained from the Bloomington Stock Center. UAS-rheb, tsc1/2, UAS-Tsc1, UAS-Tsc2, UAS-ten, UAS-atg1, and thor flies were previously described (Gao et al., 2000; Gao and Pan, 2001; Saucedo et al., 2003; Teleman et al., 2005; Scott et al., 2007). H. Steller (The Rockefeller University, New York, NY) provided NinaE RH27 flies. C. Montell (The Johns Hopkins University, Baltimore, MD) provided norpA P24 flies. T. Neufeld (University of Minnesota, Minneapolis, MN) provided atg7 d77 flies.

Genotypes

Fig. 1 shows GMR-Gal4/+; GMR-rheb, and tsc1/2 [ey-Gal4 UAS-rheb [neoFRT]828; GMR-hid[P(neoFRT)828; GMR-tsc1/2]. Fig. 2 shows ninaE-Gal4, GMR-rheb, thor, and GMR-s6k flies. Fig. 3 shows atg7, ninaE-atg1, ninaE-atg1/+; ninaE-atg1/ninaE-atg1, and ninaE-rheb/ninaE-atg1 [UAS-rheb/ninaE-atg1; ninaE-Gal4/ninaE-atg1]. Fig. 4 shows HQ120 (GMR-HQ120, HQ120, GMR-Tsc1/2 [GMR-HQ120; UAS-Tsc1 UAS-Tsc2/+] or by direct binding of TSC proteins to polyQ aggrega-

tions. However, many neural cell death models and most retinal degeneration diseases are not known to involve the formation of protein aggregates. Thus, one outstanding question was whether TOR signaling and autophagy could modulate the cellular toxicity of unaggregated proteins. The toxic rhodopsin–arrestin complexes that form as a result of phototransduction, promoting retinal degeneration in norpA mutants, provided a good test case because rhodopsin–arrestin complexes are not detected in aggregates. We found that either TOR-dependent or -independent autophagy could suppress the accumulation of rhodopsin–arrestin in norpA mutants and that either mode of autophagy activation could alleviate retinal degeneration. We believe that these data support a model in which autophagy can suppress neural degeneration by removing toxic soluble proteins as well as toxic protein aggregates. Therefore, therapy involving the inhibition of TOR or other means for inducing autophagy might be applied to neurological diseases rather generally.

TSC disease is a heritable disease caused by the hyperactivation of TOR signaling that occurs after somatic loss of heterozygosity in either Tsc2 or Tsc1. Although benign neural tumors

Figure 4. Neuronal degeneration in HQ120 flies was suppressed by overexpression of TSC1/2 or Atg1. (A) Time course of photoreceptor degeneration was determined by the optical neutralization technique. The flies were reared under a 12-h light/12-h dark cycle. Each data point was based on the examination of ≥60 ommatidia from at least four flies. Error bars indicate SD. (B–D) Retinal morphology of 10-d-old flies examined by transmission EM. HQ120 (B), HQ120;GMR>Tsc1/2 (C), and HQ120;NinaE-atg1 (D) are shown. Bar, 2 μm.
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in the photoreceptor cells, a GFP tag was added to the C terminus of Rh1 and subsequently subcloned into the pcNX vector. The constructs were injected into w1118 embryos, and transformants were identified on the basis of eye pigmentation.

Generation of transgenic Drosophila

To express MYC-tagged ATG1 under control of the ninaE (Rh1) promoter, the full-length atg1 cDNA with a C-terminal MYC tag was subcloned into the pcNX vector (Wang and Montell, 2006). To express GFP-labeled Rh1 in the photoreceptor cells, a GFP tag was added to the C terminus of Rh1 and subsequently subcloned into the pcNX vector. The constructs were injected into w1118 embryos, and transformants were identified on the basis of eye pigmentation.

EM

Adult fly heads were dissected and fixed in a solution with 2% paraformaldehyde, 4% glutaraldehyde, and 0.1 M phosphate, pH 7.4, for 12 h at
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