Autophagy occurs upstream or parallel to the apoptosome during histolytic cell death

Fatih Akdemir¹, Robert Farkas², Po Chen¹, Gabor Juhasz³, Lucia Medved’ová²,⁴, Miklos Sass⁵, Lai Wang⁶, Xiaodong Wang⁶, Suganthi Chittaranjan⁷, Sharon M. Gorski⁷, Antony Rodriguez⁸ and John M. Abrams¹, *

Histolysis refers to a widespread disintegration of tissues that is morphologically distinct from apoptosis and often associated with the stimulation of autophagy. Here, we establish that a component of the apoptosome, and pivotal regulator of apoptosis, is also required for histolytic cell death. Using in vivo and ex vivo assays, we demonstrate a global apoptogenic requirement for dark, the fly ortholog of Apaf1, and show that a required focus of dark- organismal lethality maps to the central nervous system. We further demonstrate that the Dark protein itself is a caspase substrate and find that alterations of this cleavage site produced the first hypermorphic point mutation within the Apaf1/Ced-4 gene family. In a model of ‘autophagic cell death’, dark was essential for histolysis but dispensable for characteristic features of the autophagic program, indicating that the induction of autophagy occurs upstream or parallel to histolytic cell death. These results demonstrate that stimulation of autophagy per se is not a ‘killing event’ and, at the same time, establish that common effector pathways, regulated by the apoptosome, can underlie morphologically distinct forms of programmed cell death.

KEY WORDS: Autophagy, Apoptosis, Drosophila, Histolysis, dark

INTRODUCTION

Apical and effector caspases lie at the core of the apoptotic program (Danial and Korsmeyer, 2004). Upon interaction with adaptor molecules, apical caspases are stimulated to activate effector caspases by proteolysis. dark, the Drosophila homolog of nematode Ced-4 and mammalian Apaf1, is thought to regulate the apical caspase Drice (Nc – FlyBase), through interactions involving respective caspase recruitment domains (CARD) (reviewed by Mills et al., 2005). As in mammalian systems, fly caspases are also subject to negative regulation by IAP proteins (Danial and Korsmeyer, 2004), and, among Drosophila members of this family, Diap1 (Thread – FlyBase) is known to exert important control over apoptosis (Goyal, 2001; Wang et al., 1999). This protein binds Drice and the effector caspase Drisc (Ice – FlyBase), inhibiting the activity of each via multiple mechanisms (Ditzel et al., 2003; Hays et al., 2002; Martin, 2002; Meier et al., 2000; Ryoo et al., 2002; Wilson et al., 2002; Wing et al., 2002b). Diap1 itself is under tight regulation and is effectively antagonized by proapoptotic proteins [reaper (rpr), grim, hid (also known as Wrinkled) and skl] encoded in the reaper region (Chai et al., 2003; Christich et al., 2002; Silke et al., 2004; Wing et al., 2002a; Wing et al., 2002b; Wing et al., 2001; Wu et al., 2001; Yoo et al., 2002; Zachariou et al., 2003). Together, these linked genes specify virtually all programmed cell death (PCD) in the fly embryo, as the combined deletion of these eliminates PCD at this stage (Abrams, 1999).

Three broadly conserved protein families, represented by Ced-9/Bcl2, Ced-4/Apaf1 and Ced-3/Caspase 9, define fundamental components in pathways of caspase control. However, a unified mechanism for their action in cell death remains elusive, as analogous physical interactions seen between nematode Ced-9 and Ced-4 do not occur among orthologous mammalian counterparts (Morishii et al., 1999). Instead, mammalian Bcl2 proteins indirectly engage Apaf1 by controlling the mitochondrial release of cytochrome c, which promotes the formation of a multimeric complex referred to as the apoptosome (Danial and Korsmeyer, 2004; Spierings et al., 2005). Although the fly counterparts of these genes add provocative clues, particularly with respect to the negative regulators of caspase activity (Salvesen and Abrams, 2004), they also complicate the picture, as cytochrome c appears dispensable for Drosophila Apaf1 (Dark)-dependent cell death, despite the conservation of a WD domain thought to be necessary for cytochrome c binding and regulation (Adrain et al., 1999; Dorstyn et al., 2004; Hu et al., 1998; Rodriguez et al., 1999; Zimmermann et al., 2002). Previous data from us, and from others, on viable hypomorphic alleles (Kanuka et al., 1999; Rodriguez et al., 1999; Zhou et al., 1999) have established that Dark shares functional properties with its counterparts in C. elegans, where Ced-4 is required for all PCD, and in the mouse, where context-specific apoptogenic requirements for Apaf1 are seen. However, central questions, approachable only with a null allele, remained open.

Here, we isolate a single-gene null mutation at dark and demonstrate a general requirement for this gene in PCD and stress-induced apoptosis. The role for dark in PCD was not absolute, however, as rare cell deaths were observed. We show that a required focus of dark- organismal lethality maps to the central nervous system and also describe the first hypomorphic allele within the Apaf1/Ced-4 gene family. In a model of tissue histolysis, dark was essential for cell death but dispensable for characteristic features of the autophagic program, indicating that the stimulation of autophagy

¹Department of Cell Biology, UT Southwestern Medical Center, Dallas, TX 75390, USA. ²Institute of Experimental Endocrinology, Slovak Academy of Sciences, Vlarska 3, 83306 Bratislava-Kramare, Slovakia. ³Department of Genetics, Cell Biology and Development, University of Minnesota, 6-160 Jackson Hall, 321 Church Street SE, Minneapolis, MN 55455, USA. ⁴Department of Genetics, Faculty of Science, Comenius University, 84215 Bratislava, Slovakia. ⁵Department of General Zoology, Lorand Eotvos University, Pazmany setany 1/C, H-1117 Budapest, Hungary. ⁶Department of Biochemistry, UT Southwestern Medical Center, Dallas, TX 75390, USA. ⁷Genome Sciences Centre, BC Cancer Research Centre, 675 West 10th Avenue, Vancouver, BC V5Z 1L3, Canada. ⁸Wellcome Trust, Sanger Institute, Genome Campus, Cambridge CB10 1SA, UK.

*Author for correspondence (e-mail: John.Abrams@utsouthwestern.edu)

Accepted 17 February 2006
per se is not the mechanism of cell killing but lies upstream, or parallel to dark. These data establish that common effector pathways, regulated by the apoptosome, specify apoptotic and histolytic forms of PCD.

MATERIALS AND METHODS
Mutagenesis
To isolate deletions that eliminate dark without compromising the function of adjacent neighboring genes, a P insertion associated with darkCD4 (Rodriguez et al., 1999) was remobilized and candidates were tested in trans to existing alleles and against lethal mutations in flanking genes. Promising ‘hits’ were screened by PCR. dark82 failed to complement darkCD4, but complements adjacent lethal alleles in the neighboring genes, RhoGEF and a new lethal P mutation in CG8963 that we fortuitously obtained in our first round of mutagenesis. Genomic PCR across the deletion junction and RT-PCR were used to validate the mutation and define the dark82 lesion. yw was the parental wild-type strain for molecular analysis and for ex vivo hemocyte studies. RNA extraction and QRT-PCR were conducted as described by Gorski et al. (Gorski et al., 2003). Ages at 25°C were normalized from 18°C (Park et al., 1996). Genomic PCR and RT-PCR were performed as described by Chew et al. (Chew et al., 2004), with relevant gene-specific primers.

Transgenic ‘rescue’ and genetic manipulation
Full-length dark with 8X His-tags at the N terminus and 3X Myc-tags at the C terminus was cloned into the BamHI/XhoI sites of the pFastBac1 vector (Invitrogen). The BamHI/XhoI insert was then subcloned into the pUAST vector to produce pUAST-darkN8. pUAST-darkK was generated by changing Aspartate 1292 to Alanine using a QuickChange Site-Directed Mutagenesis Kit (Stratagene). The pUAST constructs were injected into fly embryos following standard procedures to obtain transformants. Independent transgenic lines were mapped and crossed to the dark82 background. For rescue experiments, dark82CyO, actin-GFP; UAS-darkB8 or dark82CyO, actin-GFP; UAS-dark/Tub-Gal4 were crossed to dark82. The number of homozygous Flp/+; OvoD FRT2R-G13/dark82 FRT2R-G13 rescue experiments, Gal4/TM3, Sb flies (or other drivers). The number of homozygous Flp/+; OvoD FRT2R-G13/dark82 FRT2R-G13 transgenic lines were mapped and crossed to the parental wild-type strain for molecular analysis and for ex vivo hemocyte (Kit (Stratagene). The pUAST constructs were injected into fly embryos following standard procedures to obtain transformants. Independent transgenic lines were mapped and crossed to the dark82 background. For rescue experiments, dark82CyO, actin-GFP; UAS-darkB8 or dark82CyO, actin-GFP; UAS-dark/Tub-Gal4 progeny and number of heterozygous dark82/CyO, actin-GFP: UAS-dark/Tub-Gal4 progeny were counted. The percent of rescue was calculated by dividing the number of rescued dark82 homoyzogotes by the Mendelian value expected if dark82 homoyzogotes were fully viable. Similar crosses were used to obtain dark82; UAS-dark/Hml-Gal4 L3 larvae for hemocyte isolation. c81-Gal4, c833-Gal4 and Hml-Gal4 strains (Drapeau et al., 2003; Goto et al., 2003; Hrdlicka et al., 2002; Manseau et al., 1997) were obtained from the Bloomington Stock Center.

Germline clones and AO staining
The dark82 allele was recombined onto the FRT2R-G13 chromosome. To generate dark82 maternal-null embryos, the Dominant Female Sterile (DFS) technique was used, as described previously (Chou and Perrimon, 1996). hs-FIp/s; OvoD FRT2R-G13/dark82 FRT2R-G13 females were crossed with dark82/CyO, actin-GFP males to generate maternal and zygotic dark-null embryos. To detect cell death, Acridine Orange (AO) staining was carried out (Abrams et al., 1993).

Ex vivo hemocyte analyses
Wandering L3 instar larvae were prepared as described by Chew et al. (Chew et al., 2004), with the following modifications. Hemolymph was collected from six larvae and agents were added after media addition. Membrane blebbing, a characteristic feature of apoptosis, was used to quantify apoptosis. At ~6 hours post-treatment, cells were stained with a fluorescein membrane dye, 10 μM CellTracker (Molecular Probes) in DMSO, to facilitate the visualization of apoptotic membrane blebbing (without fluorescent labeling it was difficult to assess membrane blebbing owing to the phagocytic nature of hemocytes).

Immunohistochemistry and western blotting
Immunohistochemistry on dissected salivary glands was conducted as described by Farkas and Mechler (Farkas and Mechler, 2000). For actin counterstaining, fluorescein-conjugated phalloloidin (1:200; Molecular Probes), AlexaFluor488-Phalloidin or AlexaFluor546-Phalloidin (Molecular Probes) was used; for nuclear counterstaining, 0.5 μg/ml Hoechst 33258 (Calbiochem) or 1 μg/ml OliGreen (Molecular Probes); and for caspase activity, rabbit anti-cleaved caspase-3 antibody (1:500; Cell Signaling Technology). Optical sections (0.5 μm thick) were collected using a Zeiss LSM-510 Meta laser confocal microscope equipped with a 40x planapochromat oil objective. Recombinant Dark protein was prepared as described previously (Yu et al., 2005). Transgenic Dark protein was detected in extracts from adult heads, with an anti-Myc antibody at a dilution of 1:2000. Anti-Dark polyclonal antibody was used at a dilution of 1:3000.

Electron microscopy
Samples were prepared and processed for electron microscopy as described previously (Juhasz and Sass, 2005).

Visualization of MDC and GFP-LC3
Transgenic flies containing UAS-GFP-LC3 were kindly provided by the Harald Stemmark Laboratory (Rusten et al., 2004) and crossed to flies containing the salivary gland driver D59-Gal4 (Gustafson and Boulianne, 1996) (kindly provided by Carl Thummel). Salivary glands of the progeny were dissected in Drosophila Schneider’s medium (Invitrogen) and transferred to the same medium with MDC (0.1 mM) for 30 minutes at room temperature. Samples were then rinsed once and mounted (both in Schneider’s medium). Salivary glands were analyzed by fluorescence microscopy using a Zeiss Axioplan 2 microscope.

RESULTS
dark82 is null allele
To investigate the molecular genetic properties of the Drosophila apoptosome, and to illuminate possible ‘non-death’ roles for the dark gene in development, we recovered a null mutation at dark in a screen for excision derivatives of an existing P insertion (Rodriguez et al., 1999). dark82 is a 6.3-kb deletion spanning the entire open-reading frame and nearly the entire transcription unit (Fig. 1A-C). Animals homozygous for this allele arrest as late pupae and often present a characteristic dark blister located centrally along the midline. The mutation fails to complement all existing hypomorphic dark alleles, but complements flanking genes (see Materials and Methods).

Ex vivo hemocyte analyses
Wandering L3 instar larvae were prepared as described by Chew et al. (Chew et al., 2004), with the following modifications. Membrane blebbing, a characteristic feature of apoptosis, was used to quantify apoptosis. At ~6 hours post-treatment, cells were stained with a fluorescein membrane dye, 10 μM CellTracker (Molecular Probes) in DMSO, to facilitate the visualization of apoptotic membrane blebbing (without fluorescent labeling it was difficult to assess membrane blebbing owing to the phagocytic nature of hemocytes).

Immunohistochemistry and western blotting
Immunohistochemistry on dissected salivary glands was conducted as described by Farkas and Mechler (Farkas and Mechler, 2000). For actin counterstaining, fluorescein-conjugated phalloloidin (1:200; Molecular Probes), AlexaFluor488-Phalloidin or AlexaFluor546-Phalloidin (Molecular Probes) was used; for nuclear counterstaining, 0.5 μg/ml Hoechst 33258 (Calbiochem) or 1 μg/ml OliGreen (Molecular Probes); and for caspase activity, rabbit anti-cleaved caspase-3 antibody (1:500; Cell Signaling Technology). Optical sections (0.5 μm thick) were collected using a Zeiss LSM-510 Meta laser confocal microscope equipped with a 40x planapochromat oil objective. Recombinant Dark protein was prepared as described previously (Yu et al., 2005). Transgenic Dark protein was detected in extracts from adult heads, with an anti-Myc antibody at a dilution of 1:2000. Anti-Dark polyclonal antibody was used at a dilution of 1:3000.
Table 1. Tissue-specific rescue by wild-type dark and a hypermorphic allele

<table>
<thead>
<tr>
<th>Driver</th>
<th>Percentage of rescued dark82 homozygous flies</th>
</tr>
</thead>
<tbody>
<tr>
<td>UAS-darkWT.H4</td>
<td>No 0% (27)</td>
</tr>
<tr>
<td>UAS-darkWT.B6</td>
<td>No 0% (24)</td>
</tr>
<tr>
<td>UAS-darkC8</td>
<td>33% (18)</td>
</tr>
<tr>
<td>UAS-darkG6</td>
<td>23% (30)</td>
</tr>
<tr>
<td>UAS-darkWT.H4</td>
<td>Tubulin-Gal4 100% (27)</td>
</tr>
<tr>
<td>UAS-darkWT.B6</td>
<td>Tubulin-Gal4 95% (38)</td>
</tr>
<tr>
<td>UAS-darkC8</td>
<td>Tubulin-Gal4 92% (25)</td>
</tr>
<tr>
<td>UAS-darkG6</td>
<td>Tubulin-Gal4 97% (30)</td>
</tr>
<tr>
<td>UAS-darkWT.H4</td>
<td>Dal-Gal4 100% (34)</td>
</tr>
<tr>
<td>UAS-darkWT.B6</td>
<td>Dal-Gal4 96% (25)</td>
</tr>
<tr>
<td>UAS-darkC8</td>
<td>Dal-Gal4 103% (35)</td>
</tr>
<tr>
<td>UAS-darkG6</td>
<td>Dal-Gal4 95% (29)</td>
</tr>
<tr>
<td>UAS-darkWT.H4</td>
<td>Hml-Gal4 0% (22)</td>
</tr>
<tr>
<td>UAS-darkWT.B6</td>
<td>Hml-Gal4 0% (33)</td>
</tr>
<tr>
<td>UAS-darkC8</td>
<td>Hml-Gal4 29% (35)</td>
</tr>
<tr>
<td>UAS-darkG6</td>
<td>Hml-Gal4 18% (29)</td>
</tr>
<tr>
<td>UAS-darkWT.H4</td>
<td>pCNS-Gal4 (c81) 16% (62)</td>
</tr>
<tr>
<td>UAS-darkWT.B6</td>
<td>pCNS-Gal4 (c81) 18% (80)</td>
</tr>
<tr>
<td>UAS-darkC8</td>
<td>c833-Gal4 0% (23)</td>
</tr>
<tr>
<td>UAS-darkG6</td>
<td>c833-Gal4 0% (25)</td>
</tr>
</tbody>
</table>

Data from transgenic rescue experiments is summarized. Reversal of dark82 lethality was scored in contexts where tissue-specific expression of a wild-type transgene (UAS-darkWT) or a dark variant transgene (UAS-darklı) were tested. The left-hand column indicates the transgene tested in combination with the tissue ‘driver’ listed in the middle column. In each case, a single dose of the transgene and driver are tested. The right-hand column indicates the percentage of rescued animals relative to the expected Mendelian value, listed in parentheses. Note that, for each transgene, at least two independent lines were tested (H4 and B6 for UAS-darkWT, and C8 and G6 for UAS-darklı). dark82 lethality is fully rescued if UAS-darkWT is driven by Tubulin-Gal4 or by Dal-Gal4, which both confer ubiquitous expression. By contrast, no rescue is observed if UAS-darklı is combined with an embryonic CNS/larval disc driver (c833-Gal4) or a hemocyte-specific driver (Hml-Gal4). However, substantial rescue of dark82 lethality occurs when expression of UAS-darklı is restored in the post-embryonic CNS using the pCNS-Gal4 driver, also called c81-Gal4 and expressed diffusely throughout brain lobes, but not in embryos, egg chambers or imaginal discs (Drapeau et al., 2003; Manseau et al., 1997). Surprisingly, in the absence of any Gal4 driver, ‘leaky’ expression of darklı partially rescued dark82 lethality, but wild-type dark did not.

Methods). Homozygous dark82 animals were rescued to viability using a transgene containing a full-length dark cDNA (see Table 1). Hence, dark82 is a lethal, single-gene null mutation.

Figure 2. dark is essential for programmed and unprogrammed apoptosis. (A-D) Maternal and zygotic sources of dark were removed using a Dominant Female Sterile strategy (see Materials and methods). The resulting embryos lacked nearly all PCD, shown here by Acridine Orange (AO) staining (green). A and B show mid-staged embryos eliminated for maternal dark but heterozygous for zygotic dark; C and D show comparably staged embryos lacking both maternal and zygotic dark. Note that without a source of dark, embryos are head involution defective with only few AO-positive cells. (E-G) Requirement for dark in models of stress-induced cell death. Hemocytes aspirates from dark82 and wild-type (wt) wandering third instar larvae were treated with chemical stressors ex vivo and stained with CellTracker (see Materials and methods). Induction of apoptosis in wild-type (E) but not dark82 (F) hemocytes is exemplified here with micrographs taken 6 hours after Cycloheximide (CHX) treatment. (G) Quantification of apoptosis 6 hours after challenge with either CHX or a Smac mimetic (Li et al., 2004) are plotted as the incidence of cell death in percentages. Error bars indicate s.d.

Elimination of maternal and zygotic dark
Because animals homozygous for darklı survive to pupation, we used the Dominant Female Sterile technique to examine the phenotypes of animals lacking maternally supplied dark (see Materials and methods). We found normal PCD patterns in embryos that retained zygotic, but lacked maternal, dark (Fig. 2A,B). By contrast, embryos devoid of both maternal and zygotic dark were almost entirely cell death defective, with rare cell deaths noticeable in later-staged animals (Fig. 2C,D). These observations demonstrate a global need for dark in PCD. However, the requirement is not absolute, as occasional apoptotic cell deaths did occur in the complete absence of dark function. Embryos lacking maternal and zygotic dark failed to hatch and were also defective for head involution, similar to cell-death defective mutations in the Reaper region (Grether et al., 1995; White et al., 1994) and dronc (Chew et al., 2004). At the same time, gastrulation, segmental patterning and extension of the germ band appeared grossly normal in the absence of dark. Hence, to the extent that these events involve migration and/or movement, we note that the proposed role for dark in cell motility evidently does not generalize to these morphogenetic processes (Geisbrecht and Montell, 2004). We also tested larval hemocytes in ex vivo models of stress-induced cell killing (Fig. 2E-G). In contrast to wild-type counterparts, darklı hemocytes were completely resistant to a Smac mimetic, which antagonizes inhibitor of apoptosis proteins (IAPs) and is thought to simulate the action of reaper proteins (Li et al., 2004; Sélvesen and Abrams, 2004). Likewise, darklı cells were completely insensitive to the apoptogenic effects of cycloheximide, a protein synthesis inhibitor. Together, these data establish a central role for the action of dark in programmed and unprogrammed apoptosis.

Tissue-specific restoration in the CNS reverses darklı lethality
To confirm and extend these studies, we restored dark using a transgene (designated UAS-darkWT) that places a full-length cDNA under the control of the yeast-derived UAS promoter, which permits
Fig. 3. Alteration of a caspase cleavage site produces a hypermorphic Dark variant. (A) Recombinant Dark protein (lane 1) was incubated with cytosolic S20 fractions prepared from control S2 cells (lane 2) or cycloheximide (CHX)-treated S2 cells (lane 3). Asterisk denotes the small Dark C-terminal fragment after cleavage. (B) Consistent with in vitro studies (A), stimulus-dependent cleavage of Dark is detected here in Drosophila S2 cells. Samples from unchallenged (Ctrl) S2 cells or cells treated with 20 μM Cycloheximide (CHX) or 200 mJ/cm² UV were harvested after 4 hours. (C) Cleavage of Dark as seen in panel B with CHX treatment, is reversed by the caspase inhibitor z-VAD (100 μM), shown here 5 hours post-treatment. In A, B and C, Dark was visualized with an anti-Dark polyclonal antibody. (D) The cleavage site, detected in vitro at residue 1292, is shown (arrow) in the schematized domain structure of the Dark protein. (E) Illustration of the defective anatomy of darkV flies rescued by wild-type transgene expression of UAS-darkV, which mutates the caspase site mapped in D. The notum of a darkV homozygote rescued to viability by UAS-darkV, shown here next to a wild-type fly notum (left), exhibits a ‘split thorax’ phenotype and bristle abnormalities. (F) Levels of transgenic Dark protein in various UAS-dark transgenic lines in the absence of any driver or under Tubulin-Gal4 were examined by immunoblot using an anti-Myc antibody. Arrowhead denotes Dark-myc; asterisk indicates an irrelevant cross-reacting band showing equal loading on each lane. Note that the levels of wild-type Dark and DarkV are comparable when expressed from the Tubulin-Gal4 driver or when examined for basal expression. (G) Hemocyte asporates from dark2, Hml-Gal4:UAS-darkWT (Hml:darkWT) and dark2, Hml-Gal4:UAS-darkV (Hml:darkV) L3 larvae were treated with DMSO or the Smac mimetic (Li et al., 2004), a potent apoptotic inducer. Expression of UAS-darkWT in dark2 hemocytes only mildly restored apoptosis after Smac mimetic treatment. However, UAS-darkV almost completely restored this apoptotic response to dark2 hemocytes.

conditional expression when combined with tissue-specific Gal4-driver strains. Table 1 shows that, in two independently transformed lines, ubiquitous expression of wild-type dark, using either Tubulin-Gal4 or Daughterless-Gal4 drivers, completely rescued dark2 lethality. In parallel studies, the expression of UAS-darkWT in mutant hemocytes (via the Hml-Gal4 driver) did not rescue viability, but did partially restore sensitivity to Smac mimetic killing to these cells (Fig. 3G). Surprisingly, exclusive restoration of dark to the post-embryonic central nervous system using pCNS-Gal4 (also called c81-Gal4) reversed darkWT lethality, but restoration of dark to the embryonic CNS and imaginal discs (c833-Gal4 driver) did not. Although we cannot exclude the possibility that maternal dark is depleted in the CNS earlier than in other tissues, these results demonstrate that, at minimum, expression of dark in the post-embryonic CNS is necessary to reverse organismal lethality and to produce a viable adult. We also note here that male and female adults rescued by pCNS-Gal4 driven dark were sterile. However, in DAPI-stained preparations, no associated defects in germ line formation were detected at the gross morphological level.

**A caspase cleavage site in Dark confers hypermorphic gene activity when mutated**

Exploratory in vitro studies with recombinant Dark identified a putative caspase cleavage site that was mapped to Asp1292 (Fig. 3A,D). Consistent with this, studies using Drosophila S2 cells detected a cleavage of Dark that matched predictions from in vitro studies (Fig. 3B) and was caspase dependent, as it was prevented by the caspase inhibitor ZVAD (Fig. 3C). To examine the biological effects of this site in vivo, we tested a variant darkV (see Materials and methods) that substitutes Ala for Asp at position 1292. Like wild-type transformants, ubiquitous restoration of this dark variant (UAS-darkV) reversed the lethality caused by dark2 (Table 1). However, in the absence of any Gal4 driver, ‘leaky’ expression of UAS-darkV also rescued dark2 lethality but, surprisingly, wild-type dark did not (Table 1). Therefore, darkV exhibits hypermorphic gene action relative to wild-type dark. In fact, adult flies rescued to viability with darkV displayed split thorax phenotypes and bristle abnormalities in the notum (Fig. 3E) that resemble darkV homozygotes (Rodriguez et al., 1999). Together, these observations indicate that leaky expression of darkV restores gene function to null animals, not to the wild-type level but, instead, to levels comparable to those seen in darkV. Hypermorphic properties related to darkV were also noted in ex vivo hemocyte assays. Expression of the wild-type cDNA in dark2 hemocytes only mildly restored stimulus-dependent apoptosis after treatment with a Smac mimic. However, darkV almost completely restored this apoptotic response to dark2 hemocytes (Fig. 3G). We considered the possibility that altered expression of UAS-darkV might explain the hypermorphic properties conferred by darkV but, as shown in Fig. 3F, the expression levels of wild-type and variant transgenes were equal. Therefore, in studies of organismal viability and hemocyte apoptosis, darkV conferred striking hypermorphic gene activity without detectable effects upon steady-state expression. These results are consistent with negative-feedback models whereby the action of the Dark protein may be directly repressed by effector caspases, thereby setting an apoptotic threshold in cells that are specified for death.
Elimination of dark prevents salivary gland histolysis

To determine whether dark might function in autophagic cell death, we examined larval salivary glands, which normally histolyse at 16 hours after puparium formation (APF), manifesting vesicular features that are morphologically distinct from apoptosis (see Fig. 4A, Fig. 5A) (Lee and Baehrecke, 2001; Thummel, 2001). In dark mutants, these organs did not histolyse and, instead, persisted intact, even in 36-hour APF animals (Fig. 4B). Wild-type and dark glands were also stained for immunoreactivity with anti-cleaved caspase 3, an antibody that detects effector caspase activity in Drosophila tissues (Yu et al., 2002). In early pupariation stages (4 and 8 hours APF), wild-type salivary glands show little or no immunoreactivity (data not shown), but, four hours later (12 hours APF), widespread staining with anti-cleaved caspase 3 can be observed in the cytoplasm of these cells (Fig. 4C). By contrast, levels of anti-cleaved caspase 3 staining in dark~ glands were starkly attenuated for reactivity at comparable stages and later (Fig. 4D).

These defects could reflect specific functional requirements for dark in histolysis or, alternatively, could result from a more generalized arrest in prepupal development. We can exclude the latter possibility, as persisting glands were always sampled from animals that had passed through the ‘head eversion stage’ into pupation (Ashburner, 1989) and numerous associated landmarks also proceeded on schedule (see below). Like many changes that occur during metamorphosis, salivary gland histolysis is tightly controlled by ecdysone and, hence, failure to histolyse might formally derive from a disruption of this hormonal axis (Yin and Thummel, 2005). To address this possibility, we examined
ecdysone-dependent signaling events known to occur during the period from 3 to 9 hours prior to histolysis (7-13 hours APF). For example, without dark function, ecdysone receptor (EcR) and other regulatory factors, such as BFTZ-f1 (Fig. 4E), E74A (Fig. 4F) and Kruppel homolog (not shown), accumulated in the nucleus of salivary gland cells. Likewise, in a survey of transcripts that anticipate salivary gland histolysis (Gorski et al., 2003; Lee et al., 2003), gene expression profiles from wild-type and dark82 glands were highly comparable (see Fig. 4G). As an indicator of developmental progression, equivalent expression profiles (Fig. 4G) offer considerable statistical power, as a bulk analysis of 20-30 pairs of glands is represented at each time point. Therefore, by each criterion examined, hormonal signaling and associated target responses were unperturbed in dark animals. Together, these observations establish a specific requirement for the action of dark in salivary gland cell death and exclude generalized arrest or developmental delay as an explanation for defective histolysis.

**Fig. 5. Autophagy proceeds normally in dark mutant salivary glands.** (A-C) Transmission EM of salivary gland cells. (A) A cytoplasm saturated with small vesicles and an electron dense nucleus (N) are indicative of ongoing cell death in wild-type cells at 14 hours APF. By contrast, salivary gland cells appear healthy in 14-hour APF dark82 (B) and 24-hour APF dark82 (C), showing no sign of cell death (compare the appearance of the nucleus in C with the nucleus in A). Arrows indicate autolysosomes in A-C, demonstrating that dark is not required for autophagy. Insets in panel C show enlargements of representative autophagosomes (top right corner) and autolysosomes (top left corner) seen in mutant glands. N, nucleus; g, secretory granule; asterisks indicate mitochondria. Scale bars: 1 μm; 250 nm for the insets. Arrowheads in C indicate autophagosomes. (D-I) Salivary glands dissected at the indicated time points (25°C) and stained with the acidic marker monodansylcadaverine (MDC) to detect autolysosomes (Munafo and Colombo, 2001). F shows a merged image of MDC staining (red) and detection of GFP-LC3 (green) (Rusten et al., 2004), a transgenic GFP marker for autophagosomes and autolysosomes in wild-type salivary glands (14 hours APF). At this stage, prior to histolysis, the overlap between MDC and GFP-LC3 is extensive, indicating an abundance of autolysosomes. (D-G) Time course of MDC staining in wild-type salivary glands. (D) At 9 hours APF, MDC staining is barely detectable. (E) At 11 hours APF, some punctate MDC-positive staining can be observed. However, by 14 hours APF (F) and in 15-hour APF glands (G), large MDC-positive structures are very conspicuous. Likewise, in comparably staged mutant glands, prominent MDC-positive vesicles are seen, shown here at 12 hours APF (H) and in persisting salivary glands 4 hours later (I).
Stimulation of autophagy occurs normally in persisting dark glands

We performed a series of histological and ultrastructural studies of mutant glands, with the goal of determining how dark might function in the histolysis of this organ. Two hours prior to histolysis of wild-type glands, the nucleus becomes electron dense, polytene chromosomes lose definition, vesicles saturate the cytoplasm and autolysosomes are prominent (Fig. 5A) (Farkas and Sutakova, 1998; Jiang et al., 1997; Juhasz and Sass, 2005). By stark contrast, comparably aged dark glands show no signs of vesicular saturation (Fig. 5B). Similarly, pre-histolytic changes that otherwise occur in the nuclei are not seen (Fig. 5C) and, instead, features characteristic of earlier-staged nuclei are retained. Like wild-type counterparts, however, numerous autolysosomes were evident in dark glands (Fig. 5B,C), indicating that dark function is not required for autophagy per se. To extend this analysis, we confirmed that monodansylcadaverine (MDC), an acidic marker that detects autolysosomes (Munafo and Colombo, 2001), overlapped with the signal derived from GFP-LC3 (Rusten et al., 2004), a transgenic marker of autophagy (Fig. 5F). Next, we established that, in wild-type salivary glands, dramatic accumulation of MDC staining anticipates PCD several hours prior to overt histolysis (Fig. 5D-G). We applied this methodology in dark animals and, likewise, observed a comparable abundance of MDC-stained structures in mutant glands (Fig. 5H,I), indicating that stimulation of autophagy, which normally anticipates histolysis, is not dependent on dark activity. Therefore, in this tissue, the action of dark in histolysis functions downstream of, or parallel to, an autophagic program.

DISCUSSION

Here, we show that dark encodes generalized functions in PCD. Loss of maternal and zygotic product caused profound defects, abolishing nearly all apoptotic deaths in the embryo. Likewise, elimination of zygotic dark prevented the histolytic death of salivary gland cells and also reversed drug-induced killing of hemocytes. These results establish widespread functions for dark in distinct models of programmed and stress-induced cell death. Moreover, because both apoptotic and histolytic forms of cell death were affected, it is clear that common effector pathways regulated by the apoptosome can specify apoptotic and non-apoptotic forms of PCD. The role for dark in PCD is not absolute, however, as rare apoptotic cell deaths were observed in animals lacking both the maternal and zygotic product. Although reminiscent of phenotypes associated with complete deletions in the Reaper region, loss of dark did not appear to perfectly phenocopy these, as occasional apoptotic cell deaths were observed. To substantiate this idea, we carefully compared the incidence of dark-independent cell deaths to the rare cell deaths that occur in H99 homozygous embryos. Among animals lacking both maternal and zygotic dark, an average of 8.9±2.0 cell deaths were found in late embryonic stages. However, only 3.1±2.1 cell deaths were found in comparably staged H99 embryos. Hence, in this respect, animals devoid of dark emulate cell death defects seen in animals lacking dronc (Xu et al., 2005). Together, these observations establish that, for a small population of embryonic cells, apoptotic activators in the reaper region can specify apoptosis without engaging the fly apoptosome. Similar pathways might occur in post-embryonic stages, but we caution against deriving firm conclusions in unaffected larval tissues, given the caveats relating to perdurance of maternally derived product.

Unlike its counterparts in the worm or the mouse, genetic elimination of dark produced a strictly lethal phenotype. Because ubiquitous and ‘driver-specific’ expression of a dark transgene complemented this phenotype, it was possible to map the focus of genetic activity responsible for restoring viability. We found that dark lethal lethality was reversed when expression was restored to cells of the post-embryonic CNS, but that complementation failed if dark was restored to hemocytes or imaginal discs. These results highlight essential functions for zygotic dark in the post-embryonic CNS and suggest that the action of this gene within other tissues may not be necessary for viability. Transgenic complementation also proved to be an effective means for distinguishing the wild-type gene action from that of derivatives with altered activities. By this approach, we determined that dark encodes striking hypermorphic activity without affecting transgenic expression levels. As dark is mutated at a caspase cleavage site (Fig. 3A-D), the data are consistent with negative-feedback models whereby the action of Dark is directly repressed by effector caspases, perhaps setting an apoptotic threshold in cells that are specified to die. These findings describe the first hypermorphic point mutation among all known alleles in the ced-4/Apaf1 gene family, and raise intriguing possibilities for investigating how life histories and stress responses might be impacted in adults with excessive apoptosomal activity. It is worth noting that, unlike cultured cell models, where full-length dark exhibits mild killing activity (Rodriguez et al., 1999), we found no evidence of dominant phenotypes associated with the forced overexpression of either the wild-type or the variant transgenes in tissues presented here (Fig. 3), or in other tissues, such as the eye (not shown). The different effects seen in culture cells versus transgenic animals might reflect authentic context-specific variance, or, alternatively, there may be a mild killing activity that does not manifest as a gross phenotype in the animal. Nevertheless, at least for most tissues and cells, it is unlikely that the levels of Dark protein alone qualify as a determinant of apoptosome activity. This inference, together with studies that exclude a fundamental requirement for Drosophila cytochrome c in formation of the apoptosome (Yu et al., 2005) or in models of apoptosis (Dorstyn et al., 2004; Zimmermann et al., 2002), suggests that, to function properly, Dark must be activated through an unknown mechanism.

Regression of Drosophila salivary glands in pupal development is a classic model of histolytic cell death, and dying cells in this gland appear morphologically distinct from cells undergoing apoptosis, indicating that novel cell death pathways may control forms of histolytic cell death (reviewed by Thummel, 2001). We assessed morphological, ultrastructural and molecular indicators to establish that, without dark, developmental progression was unperturbed, histolytic regression of this organ failed and salivary gland cells remained morphologically intact. Our results clearly establish a requisite function for Dark in the histolysis of salivary gland cells, despite the fact that PCD of these cells appears dissimilar from classical apoptosis. These observations are consistent with effects produced by p35, a broad-spectrum caspase inhibitor (Jiang et al., 1997; Lee and Baehrecke, 2001; Martin and Baehrecke, 2004), and with animals mutated for the apical caspase dronc (Daish et al., 2004). Because apoptotic and histolytic forms of cell death are similarly impacted by the same mutation, we conclude that common effector pathways, regulated by the apoptosome, underlie morphologically distinct forms of PCD.

The induction of autophagy that anticipates salivary gland histolysis may act as part of a novel killing mechanism in these cells (Lee and Baehrecke, 2001; Myohara, 2004; Thummel, 2001), and in mammalian cell death models as well (Shimizu et al., 2004; Yu et
al., 2004). However, in other circumstances, ‘self-digestion’ clearly promotes survival when apoptosis is prevented (Lum et al., 2005), and, consequently, it is important to understand how links between autophagy and cell death may instruct cell fates (Levine and Klionsky, 2004). As dark organs do not regress like their wild-type counterparts, dark animals afford a unique opportunity to dissect the relationship between histolysis and autophagy. Because the stimulation of autophagy continued in glands that failed to histolyse, we suggest that induced autophagy per se is not the ‘lethal event’ mediating histolysis of this organ. Instead, the epistasis experiments described here demonstrate that the induction of autophagy lies upstream of, or parallel to, the apoptosis in this model of histolytic cell death.

We gratefully acknowledge support to J.M.A. from the NIH (GM072124), and VEGA (2/0325/03) and APVT (51-027402) grants to R.F., and an NKFP grant (1/a005/04) to M.S. We are also grateful to Kathrine Galindo for germ line transformations, to T. E. Rusten and H. Stenmark for GFP-LC3 flies, and to Margaret Hickson for administrative support.

References


Autophagy is upstream of/parallel to the apoptosome.


