Programmed cell death mechanisms of identifiable peptidergic neurons in Drosophila melanogaster

Youn-Jeong Choi, Gyunghee Lee and Jae H. Park*

The molecular basis of programmed cell death (PCD) of neurons during early metamorphic development of the central nervous system (CNS) in Drosophila melanogaster are largely unknown, in part owing to the lack of appropriate model systems. Here, we provide evidence showing that a group of neurons (vCrz) that express neuropeptide Corazonin (Crz) gene in the ventral nerve cord of the larval CNS undergo programmed death within 6 hours of the onset of metamorphosis. The death was prevented by targeted expression of caspase inhibitor p35, suggesting that these larval neurons are eliminated via a caspase-dependent pathway. Genetic and transgenic disruptions of ec dysone signal transduction involving ec dysone receptor-B (EcR-B) isoforms suppressed vCrz death, whereas transgenic re-introduction of either EcR-B1 or EcR-B2 isoform into the EcR-B-null mutant resumed normal death. Expression of reaper in vCrz neurons and suppression of vCrz-cell death in a reaper-null mutant suggest that reaper functions are required for the death, while no apparent role was found for hid or grim as a death promoter. Our data further suggest that diap1 does not play a role as a central regulator of the PCD of vCrz neurons. Significant delay of vCrz-cell death was observed in mutants that lack dronc or dark functions, indicating that formation of an apoptosome is necessary, but not sufficient, for timely execution of the death. These results suggest that activated ec dysone signaling determines precise developmental timing of the neuronal degeneration during early metamorphosis, and that subsequent reaper-mediated caspase activation occurs through a novel DIAP1-independent pathway.

KEY WORDS: Corazonin, Programmed cell death, Metamorphosis, Ecdysone receptor, Reaper, Drosophila

INTRODUCTION

In holometabolous insects that develop through complete metamorphosis, significant behavioral changes are observed from juveniles to adults. For example, Drosophila larvae display simple behaviors, including feeding, crawling and defensive thrashing, whereas adult flies lead more complicated lifestyles that involve foraging, flying, mating and aggression in order to survive and fulfill successful reproduction. This type of behavioral transition is accompanied by substantial reorganization of the nervous system, which establishes adult-specific neural circuitry, thereby accommodating new lifestyles (Truman et al., 1993; Levine et al., 1995; Consoulas et al., 2000; Tissot and Stocker, 2000). During metamorphosis, larval neurons face mainly two different fates: remodeling or programmed cell death (PCD). The former is a recycling process of persistent neurons and is characterized primarily by significant modifications in synaptic architectures, resulting from withdrawal of larval-specific connections, followed by reconnection with new targets (e.g. Kraft et al., 1998; Lee et al., 2000b). By comparison, other neurons are scheduled to die via developmentally regulated genetic programs, as their functions are no longer required for ensuing life stages.

Several studies have implicated ecdysone as a central endocrine regulator that initiates genetic programs orchestrating overall reorganization processes of the insect nervous system during metamorphosis (Truman et al., 1993). For example, genetic analyses have shown that ec dysone receptor activities are essential for cell-autonomous remodeling of mushroom body γ-neurons and SCP-immunoreactive (IR) neurosecretory cells (Schubiger et al., 1998; Schubiger et al., 2003; Lee et al., 2000b). In addition to the remodeling, ecdysone has been shown to cause apoptosis of obsolete larval neurons. In a moth, identified motoneurons innervating larval proleg muscles are degenerated in response to a prepupal ecdysone surge (Weeks, 2003). Treatment of isolated motoneurons with ecdysone in vitro also causes the death, suggesting that ecdysone directly induces a cell-autonomous death program (Streichert et al., 1997).

Although underlying molecular mechanisms for post-embryonic neuronal PCD are largely unknown, extensive genetic studies have identified key molecular players that either enhance or suppress PCD occurring in developing Drosophila embryos and compound eyes (reviewed by Cashio et al., 2005; Kornbluth and White, 2005). Apoptotic death is a direct consequence of massive destruction of cellular components mediated by specialized proteolytic enzymes: caspases (reviewed by Salvesen and Abrams, 2004). In living cells, the caspases are inactivated and/or degraded by the action of Drosophila inhibitor of apoptotic protein 1 (DIAP1) through forming a complex with caspases (Meier et al., 2000; Muro et al., 2002; Wilson et al., 2002). When cells are challenged with death stimuli, death activators (collectively referred to as RHG) encoded by reaper (rpr), head involution defective (hid; W – FlyBase) and grim, which are defined by deficiency Df(3L)H99 (White et al., 1994; Grether et al., 1995; Chen et al., 1996), bind to DIAP1, liberating caspases from the DIAP1-caspase complexes, resulting in the activation of caspases (Wang et al., 1999; Goyal et al., 2000). Physical interactions between RHG proteins and DIAP1 are also known to downregulate DIAP1 levels via ubiquitin-mediated self-degradation of DIAP1, which further ensures an irreversible death pathway (Ryoo et al., 2002; Yoo et al., 2002). Products of two additional pro-apoptotic genes, sickle and jafrac2, are also implicated as DIAP1 antagonists (Christich et al., 2002; Srinivasula et al., 2002; Tenev et al., 2002; Wing et al., 2002).

Fundamental molecular cell death mechanisms just described appear to be conserved in the tissues that require ec dysone for their death at a precise developmental stage. Larval salivary glands and

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midgut are degenerated in response to an ecdysone stimulus during metamorphosis in which ecdysone activates transcription of \( rpr \) and \( hid \) directly, or indirectly via ecdysone-responsive transcription factors such as Broad Complex (BR-C), E74 and E93 (Jiang et al., 2000; Lee et al., 2002). Premature destruction of these tissues throughout larval growth is prevented by DIAP1, until ecdysone-induced RPR or HID proteins overcome the inhibitory action of DIAP1 (Yin and Thummel, 2004).

During prepupal stage, a number of unwanted larval neurons are removed from the CNS in Drosophila. Neuronal degeneration is particularly prominent in the abdominal ganglion, leading to significant shrinkage of this neuropil (Truman, 1990; Truman et al., 1993). Although ecdysone is an important developmental cue for the PCD of obsolete larval neurons in the CNS are significant shrinkage of this neuropil (Truman, 1990; Truman et al., 2000; Lee et al., 2002). Premature destruction of these tissues throughout larval growth is prevented by DIAP1, until ecdysone-induced RPR or HID proteins overcome the inhibitory action of DIAP1 (Yin and Thummel, 2004).

The following deficiencies were used to generate \( rpr \)- and \( hid \)-null mutations: \( Df(3L)XR38 \), \( Df(3L)H99 \) and \( Df(3L)X14 \) (for short, \( XR38 \), \( H99 \), and \( X14 \), respectively). Homozygous deletion of the \( rpr \) locus was obtained by combining \( H99 \) with \( XR38 \) in trans as described (cf. Peterson et al., 2002). Flies lacking \( hid \) functions were produced by transallelic combination of \( H99 \) (or \( X14 \)) with \( hid^{4004} \) allele (Grether et al., 1995). Although most of the \( hid \) mutants are embryonic lethal, a few escapers enabled us to assess vCrz neuronal death in these mutants (Peterson et al., 2002).

Null mutations of caspase-encoding \( dronc \) (\( Ne \) – FlyBase) gene were obtained by transallelic combinations of \( dronc^{23} \) (or \( dronc^{25} \)) with \( dronc^{45} \) (Chew et al., 2004; Xu et al., 2005). Two thread (th, \( diap1 \)) alleles, \( th^{2} \) (loss-of-function) and \( th^{25} \) (gain-of-function), were used in some experiments (Lisi et al., 2000). The mutant alleles used in this study are summarized in Table 1.

Transgenic lines
To construct P-element containing \( dronc \) promoter fused to the gal4-coding sequence (hereafter referred to as \( Crz-gal4 \)), a genomic region upstream of the \( Crz \) gene (~1155 to +78 relative to the transcription start site +1) (Choi et al., 2005) was amplified by PCR, and subcloned into pBluescript at the XmaI site, from which an XbaI-EcoRI fragment was inserted into pPTGAL vector (Sharma et al., 2002). For \( rpr-gal4 \) construct, previously defined 1.3 kb \( rpr \) upstream sequence (Jiang et al., 2000) was inserted into pPTGAL at BglII/EcoRI sites. Each resulting vector was mixed with \( pUCh\Delta n2.3 \) helper plasmid (Laski et al., 1986) and injected into the \( y^{+} \) or \( w^{1118} \) embryos for germ-line transformation (Rubin and Spradling, 1982). \( Crz-gal4 \) (S2b, T2a) and \( rpr-gal4 \) (III) lines were used in this study.

X-gal histochemistry and immunohistochemistry (IHC)
To detect \( \beta \)-galactosidase expression, CNSs were fixed in 0.2% glutaraldehyde, washed in PBS and then incubated in 5-bromo-4-chloro-3-indolyl-\( \beta \)-D-galactoside (X-gal) solution at 37°C overnight. The tissues were rinsed in PBS, dehydrated in ethanol and mounted in glycerol (e.g. Park et al., 2000).

Whole-mount \( Crz \) immunohistochemistry was performed as described previously (Choi et al., 2005). The anti-Crz was previously referred to as anti-CAP, which was raised against \( Crz \)-Associated Peptide within the precursor (Choi et al., 2005). To co-localize \( Ecr \)-immunoreactivity (IRy) in \( Crz \) neurons, rabbit anti-\( Crz \) and mouse monoclonal anti-\( EcR \) (15G1a) or anti-\( CAP \), which was raised against \( Crz \)-Associated Peptide within the precursor (Choi et al., 2005). The anti-Crz was previously referred to as anti-CAP, which was raised against \( Crz \)-Associated Peptide within the precursor (Choi et al., 2005).

### Table 1. Mutant alleles used in this experiment

<table>
<thead>
<tr>
<th>Locus</th>
<th>Allele</th>
<th>Type of mutation</th>
<th>Ref.</th>
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<tbody>
<tr>
<td><strong>EcR</strong></td>
<td>( EcR^{17} )</td>
<td>Amorphic (A isoform)</td>
<td>Carney et al. (2004)</td>
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<td></td>
<td>( EcR^{554} )</td>
<td>Amorphic (A, B1, B2)</td>
<td>Bender et al. (1997)</td>
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<td></td>
<td>( EcR^{55} )</td>
<td>Amorphic (B1)</td>
<td>Bender et al. (1997)</td>
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<td></td>
<td>( EcR^{99} )</td>
<td>Amorphic (B1, B2)</td>
<td>Schubiger et al. (1998)</td>
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<tr>
<td><strong>BR-C</strong></td>
<td>( br^{c} )</td>
<td>Amorphic</td>
<td>Belyaeva et al. (1980)</td>
</tr>
<tr>
<td></td>
<td>( br^{5} )</td>
<td>Amorphic</td>
<td>Belyaeva et al. (1980)</td>
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<tr>
<td></td>
<td>( rbp^{5} )</td>
<td>Hypomorphic</td>
<td>Belyaeva et al. (1980)</td>
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<tr>
<td><strong>Cell death</strong></td>
<td>( XR38 )</td>
<td>Deletion (( rpr ), sickle)</td>
<td>Peterson et al. (2002)</td>
</tr>
<tr>
<td></td>
<td>( hid^{6014} )</td>
<td>Deletion (( hid ), grim, ( rpr ))</td>
<td>White et al. (1994)</td>
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<tr>
<td></td>
<td>( X14 )</td>
<td>Deletion (( hid ))</td>
<td>White et al. (1994)</td>
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<td><strong>diap1</strong></td>
<td>( Df(3L)brm11 )</td>
<td>Deletion</td>
<td>Brizuela et al. (1994)</td>
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<td>( th^{4} )</td>
<td>Amorphic</td>
<td>Lisi et al. (2000)</td>
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<td></td>
<td>( th^{25} )</td>
<td>Hypermorphic</td>
<td>Lisi et al. (2000)</td>
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<tr>
<td><strong>dronc</strong></td>
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<td>Amorphic</td>
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<tr>
<td><strong>dark</strong></td>
<td>( dark^{CD4} )</td>
<td>Amorphic</td>
<td>Rodriguez et al. (1999)</td>
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</table>
Neuronal programmed death in Drosophila

RESULTS

Programmed death of vCrz neurons

Spatial Crz expression patterns change significantly during metamorphosis as previously reported (Choi et al., 2005). In third-instar larval CNSs, Crz gene products are detected in three pairs of DL neurons and in a pair of DM neurons in the brain, and in eight pairs of symmetrically positioned neurons (vCrz) in the ventral nerve cord (VNC) (Fig. 1A,C) (Choi et al., 2005). In the CNSs taken from pupae aged for ~36 hours after pupariation formation (APF), Crz transcripts are found in 6-8 cells per hemi-brain (Fig. 1B), but none in the VNC. When immunohistochemistry was performed at an earlier stage (12-24 hours APF), protocerebral Crz-IR patterns remain unchanged from their larval patterns (arrowheads in Fig. 1D), while no vCrz neurons are visible (arrow in Fig. 1D). These temporal expression data suggest that adult-like protocerebral Crz neurons have been established between 24-36 hours APF, while vCrz expression disappeared within 12-24 hours APF.

The loss of vCrz expression could be due to programmed death of these neurons. We tested this possibility by transgenic rescue of cell death using gal4/UAS system (Phelps and Brand, 1998). As a preliminary step, we tested fidelity of the Crz-gal4 driver. As shown in Fig. 1E, Crz-gal4-driven GFP signals are completely overlapped with Crz-IRy in third-instar larval CNS. lacZ-reporter expression also faithfully recapitulates endogenous Crz expression in all life stages (Fig. 2; data not shown), suggesting that the 1.2 kb upstream sequence contains cis-elements necessary for appropriate control of spatial and developmental Crz expression.

Using Crz-gal4 driver, we induced expression of a caspase inhibitor, p35 (Hay et al., 1995), to test whether p35 can prevent cell death, thereby maintaining Crz expression in pupal VNC. Thus, a Crz-gal4, UAS-p35 double homozygous strain was crossed to the UAS-lacZ, and then the progeny were processed for X-gal histochemistry. Remarkably, all vCrz neurons marked by lacZ expression are persistently present even at 24 hours APF (Fig. 2B, compare with 2A). These data strongly support that the loss of vCrz expression during pupal development is due to caspase-dependent cell death, not due to transcriptional silencing of the Crz gene.

Developmental timing of vCrz neuronal death

To determine developmental clock of the vCrz neuronal death, lacZ-reported Crz expression was examined in various prepupal stages. Elimination of vCrz neurons occurs progressively over a ~2- to 6-hour period after pupariation (Fig. 2C-F). At 2 hours APF, one or two cells are undetectable (Fig. 2D), suggesting that execution of the death has begun in some cells at around this stage. At 3 hours APF, ~40% of the neurons are lost in a random fashion, and staining in the projections are fainter and discontinuous, leaving broken line-like appearance (arrow in Fig. 2E). This perhaps reflects phagocytic elimination of non-functional cellular components possibly by glial cells (e.g. Sonnenfeld and Jacobs, 1995; Watts et al., 2004). At 6 hours APF, most of X-gal signals are undetectable, except for a few
Ecdysone signaling initiates the death program in vCrz neurons

As the beginning of vCrz death is approximately coincident with a surge of ecdysone at pupariation (Riddiford, 1993), and the ecdysone is a key endocrine signal orchestrating overall metamorphic reformation of the CNS in insects including Drosophila (Weeks, 2003), ecdysone could be a developmental cue, activating genetic death program in doomed vCrz neurons. It is well documented that ecdysone signal is transduced by a heterodimeric receptor complex consisting of EcR and ultraspireacle (reviewed by King-Jones and Thummel, 2005). The EcR-encoding gene produces three isoforms (A, B1 and B2) via usage of different promoters and alternative splicing, which share common C-terminal ligand and DNA-binding domains but variable N termini (Talbot et al., 1993).

Recently, Cherbas et al. (Cherbas et al., 2003) developed two dominant-negative (DN) forms of EcR-B1 (B1F645A and B1W650A) that lack transcriptional activator functions, but still retain DNA-binding ability. Ectopic expression of these mutant variants effectively blocked ecdysone-led physiological processes, perhaps via competitively inhibiting wild-type receptor functions (Cherbas et al., 2003). This prompted us to test whether ectopic EcR-B1DN expression interferes with normal vCrz-cell death. For this, progeny from UAS-lacZ, Crz-gal4 × UAS-EcR-B1F645A (or UAS-EcR-B1W650A) were subjected to X-gal histochemistry. Intriguingly, all of vCrz neurons are detectable at 12 hours APF (compare Fig. 4B,C with 4A), showing that both EcR-B1DNs are (equally) capable of blocking vCrz PCD. The results strongly support our hypothesis that EcR-mediated signaling plays a decisive role in the initiation of death pathway within vCrz neurons.

EcR-B isoforms are major players for vCrz PCD

Distinct temporal expression profiles of each EcR-isoform suggest that each isoform exhibits developmental stage-specific functions for adult CNS formation during metamorphosis (Truman et al., 1994). For example, EcR-B-isoforms are involved in modifications of some larval neurons during early metamorphosis (Lee et al., 2000b; Schubiger et al., 2003). To determine types of EcR involved in vCrz-cell death, we examined isoform-specific immunoreactivity in vCrz neurons, except for the EcR-B2 because of lack of available antibody. Consistent with a previous report (Truman et al., 1994), widespread EcR-B1-IRy was observed in white prepupal CNS (Fig. 4D), whereas EcR-A-IRy was almost undetectable (data not shown). Furthermore, EcR-B1-IRy was evident in the nuclei of vCrz neurons (Fig. 4D), implicating a role of the EcR-B1 as a signal transducer for the PCD of vCrz.

To gain more insight into isoform-specific functions, we examined Crz-IRy in various EcR loss-of-function mutants. In animals heterozygous for the EcR-null mutant allele (EcR99; EcRM554fs) that lacks one copy of all EcR isoforms (Bender et al., 1997), Crz immunohistochemistry results indicated normal cell death, suggesting that a half dose of the EcR is sufficient for mediating vCrz-cell death (data not shown, n=5). Consistent with the absence of EcR-A-IRy, an EcR-A-null mutation (EcR122EcR855fsh) did not affect normal vCrz PCD (compare Fig. 4F with 4E). Therefore, we conclude that EcR-A isost is not a signal transducer for this type of cellular event.

As documented previously, animals carrying a null mutation for both EcR-B1 and EcR-B2 were generated by a trans-heterozygous combination of EcR8 and EcR8 alleles (Schubiger et al., 1998). Although most of mutant animals are developmentally arrested during the course of larval growth, a few escapers develop into prepupae (Schubiger et al., 2003), thereby permitting us to assess vCrz-cell death in this genetic background. Remarkably, Crz immunohistochemistry revealed ~12 vCrz neurons at stages when vCrz neurons were normally absent (compare Fig. 4G and Fig. 5A with Fig. 4E), suggesting that the death pathway in the majority of vCrz neurons is unable to proceed in the absence of EcR-B.
receptors. Therefore, our histological and genetic evidence together demonstrates that EcR-B isoforms play significant roles for vCrz cell death.

**Both EcR-B1 and EcR-B2 are involved in vCrz PCD**

We further determined whether both EcR-B1 and EcR-B2 are required or whether either of them is sufficient for vCrz PCD. To test this, an EcR-B1-specific mutant (EcR-B1<sup>QR50st</sup>/EcR-B1<sup>QR31</sup>) was examined for Crz-IR<sup>y</sup> (Bender et al., 1997). Surprisingly, complete lack of EcR-B1 showed no deficit in vCrz PCD (Fig. 4H). This result may suggest that only EcR-B2 is necessary for the death. Alternatively, EcR-B1 and EcR-B2 may have redundant functions, so that either isoform alone is sufficient for normal PCD.

To address this issue, it would be necessary to analyze EcR-B2 specific mutants. As such mutants are unavailable, we employed transgenic rescue of the EcR-B mutant. For this attempt, we generated y<sup>+</sup>; EcR<sup>VR11</sup>/CyO, y<sup>+</sup>; UAS-EcR-B1 (or EcR-B2) and y<sup>+</sup>; EcR<sup>VR11</sup>/CyO, y<sup>+</sup>; Crz-gal4 strains. These lines were crossed with each other and F1-larvae carrying y marker [i.e. EcR<sup>VR11</sup>/EcR<sup>VR10</sup>]. Crz-gal4/UAS-EcR-B1 (or B2) were collected and dissected after complete apolysis (separation of the old cuticle from the underlying epidermis) for Crz immunohistochemistry. As individual CNS morphology was variable depending on their developmental progress, the CNSs were classified as ‘early’, ‘intermediate’ or ‘late’ phenotypes (Cf. Schubiger et al., 2003). In the ‘early’ group, CNSs retain white prepupa-like morphology in which the optic lobes are not yet extended and subesophageal ganglia are broadly attached to the VNC. In the ‘late’ group, optic lobes are highly developed, and areas between the subesophageal ganglia and VNC begin to constrict; this is nearly equivalent to wild-type at 12 hours APF (Truman et al., 1993). In the ‘intermediate’ group, CNSs show various levels of development between ‘early’ and ‘late’ groups.

Crz immunohistochemistry revealed significant differences between EcR-B mutant and transgene-rescued lines. Complete lack of PCD was seen in 18% of the EcR-B mutant CNSs, and partial cell death in the remaining 82% of specimens. Overall, 75% of vCrz neurons did not undergo PCD in the EcR-B mutant (Fig. 5A). By contrast, expression of EcR-B1 or EcR-B2 in the mutant restored complete cell death in 73% or 87% of tissues, respectively, while four to 11 neurons were detectable in the remaining specimen (Fig. 5B,C). These data suggest that either EcR-B1 or EcR-B2 alone is capable of mediating PCD of vCrz neurons, and support the idea that EcR-B1 and EcR-B2 have redundant functions for this purpose.

**Reaper (rpr) is a proapoptotic executor of vCrz PCD**

The pro-apoptotic genes rpr, hid and grim, defined by H99 deletion, are well-known death activators in Drosophila (White et al., 1994). As rpr and hid have been shown to promote ecdysone-mediated PCD of the salivary glands and midgut (Yin and Thummel, 2004), we hypothesize that one or both of these genes might induce vCrz PCD.

The PCD of vCrz neurons was unaffected by heterozygous H99 deletion, suggesting that one copy of the wild-type rpr, hid and grim alleles is sufficient for inducing vCrz-cell death (Fig. 6A). Heterozygosity for XR38 deletion, which removes rpr and sickle (Peterson et al., 2002; Wing et al., 2002), also did not affect normal PCD (Fig. 6B). Intriguingly however, approximately seven pairs of vCrz neurons survived in a rpr-null mutant (XR38/H99) (Fig. 6C, D).
Expression in the same mutant background (n=2228 in abdominal ganglionic region (circle in Fig. 6F), while the sense hybridization to wild-type prepupal CNS. At 1.5 hours APF, tissue. Having validated the expression, suggesting that hybridization signals were nearly blank in the entire larval CNS, larva (arrowheads in Fig. 6E). Except for these cells, in situ hybridization signals seemingly in vCrz neurons in the third-instar type (data not shown), we suppose that might not be involved in vCrz PCD.

To determine cell-autonomous roles of rpr, we investigated whether rpr is expressed in vCrz neurons by in situ hybridization. To validate our rpr cRNA probe, in situ hybridization was performed on the CNSs taken from the progeny of [Crz-gal4, UAS-p35 × UAS-rpr] cross. In this context, rpr transcripts are overproduced in Crz neurons but rpr-induced death is suppressed by co-expression of the p35. As a result, we detected faint but distinct hybridization signals in vCrz neurons in wild type (data not shown), we suppose that grim might not be involved in vCrz PCD.

By contrast, vCrz neurons in mutants that lack hid functions (X14/hid and H99/hid) (Grether et al., 1995; Peterson et al., 2002) showed normal PCD (Fig. 6D, and data not shown), suggesting that hid is not a death promoter for vCrz neurons. Owing to a lack of specific mutants, possible roles for grim in situ hybridization signals were hardly detectable in larval as well as early prepupal vCrz neurons in wild type (data not shown), we suppose that grim might not be involved in vCrz PCD.

To detect rpr expression in a more sensitive manner, we generated rpr-gal4 transgenic flies. Previously, the 1.3 kb rpr upstream sequence was shown to contain an edcsyne response element (EcRE) and to be sufficient for edcsyne-dependent expression in salivary glands (Jiang et al., 2000). When F1 progeny from rpr-gal4 × UAS-mCD8-GFP cross were processed for Crz immunohistochemistry, 17 out of 80 vCrz neurons (17 out of 177) examined (Fig. 6G). Remarkably, Crz immunohistochemistry revealed ~10% of vCrz neurons (± s.d.) are in parentheses. The CNSs belonging to the ‘E’ group were not found in the EcrB2 rescue group. Representative images taken from the ‘I’ group are shown in the left. Scale bar: 100 μm.

Numbers of tissues examined in each category are noted on the right of each bar (N), and mean numbers of vCrz neurons (± s.d.) are in parentheses. The CNSs showing no cell death (open bar), partial (gray bar), or complete death (black bar). As described in the text, the CNSs were grouped into ‘E’ (Early), ‘I’ (Intermediate), or ‘L’ (Late), depending on their developmental status.

The histograms indicate percentages of the CNSs expressing rpr in situ hybridization and Crz immunohistochemistry simultaneously to see if endogenous rpr mRNAs are also expressed in vCrz neurons prior to death. At 1.5 hours APF, rpr in situ hybridization signals were detectable in ~10% of vCrz neurons (17 out of 177) examined (Fig. 6G). Owing to a lack of specific mutants, possible roles for grim in situ hybridization signals were hardly detectable in larval as well as early prepupal vCrz neurons in wild type (data not shown), we suppose that grim might not be involved in vCrz PCD.

n>5), and a similar result was obtained by Crz-gal4-mediated GFP expression in the same mutant background (n=4, data not shown). These data strongly support a crucial role that rpr plays in the destruction of vCrz neurons.

We applied rpr-gal4 to detect expression in a more sensitive manner, we generated rpr-gal4 transgenic flies. Previously, the 1.3 kb rpr upstream sequence was shown to contain an edcsyne response element (EcRE) and to be sufficient for edcsyne-dependent expression in salivary glands (Jiang et al., 2000). When F1 progeny from rpr-gal4 × UAS-mCD8-GFP cross were processed for Crz immunohistochemistry, 17 out of 80 vCrz neurons (17 out of 177) examined (Fig. 6G). Owing to a lack of specific mutants, possible roles for grim in situ hybridization signals were hardly detectable in larval as well as early prepupal vCrz neurons in wild type (data not shown), we suppose that grim might not be involved in vCrz PCD.
diap1 is not required for survival of vCrz neurons

Although vCrz-cell death is most likely to be a cellular response to an ec dysone surge occurring at pupariation, this event does not occur prematurely during ecdysone-led larval-to-larval moltings (Riddiford, 1993). This could be due to anti-apoptotic factors that counteract the pro-apoptotic machinery in larval vCrz neurons. The best candidate for this role is diap1, the anti-apoptotic activity of which comes from inhibition of caspase activity (reviewed by Bergmann et al., 2003). If diap1 is important for the survival of vCrz neurons during larval growth, then these larval neurons would contain high levels of DIAP1. Our immunohistochemistry, however, did not detect any DIAP1-IRy within larval vCrz neurons of wild type (data not shown, n=12). Despite this, as undetectable levels of DIAP1 still could be sufficient for this role, we attempted to knockdown diap1 transcript levels via RNA interference (RNAi). For this, progeny from symUAS-diap1RNAi × UAS-mCD8-GFP; Crz-gal4 cross was examined for GFP signals. Such a transgenic manipulation was intended to produce double-stranded RNAs from complementary RNAs symmetrically transcribed from the diap1 cDNA, which then mediate degradation of diap1 mRNA specifically in Crz neurons (Giordano et al., 2002; Huh et al., 2004). Our data showed that GFP expression at 1 hour APF in diap1RNAi was essentially the same as that in wild type (compare Fig. 7B with 7A), indicating that diap1-knockdown did not cause premature cell death. Similar results were obtained when two copies of the Crz-gal4 transgene were employed to increase diap1RNAi dose or by heat-shock-induced diap1RNAi (data not shown) (cf. Yin and Thummel, 2004).

As the negative results could be due to the lack of effective diap1RNAi, we checked the validity of symUAS-diap1RNAi in salivary gland PCD. In doing so, the 34B-gal4; UAS-GFP (salivary gland-specific driver) (Yin and Thummel, 2004) was crossed to the symUAS-diap1RNAi, and then GFP signals were examined in white hybridization signals are indicated by arrowheads or by a circle. (G) Double labeling of wild-type CNS with rpr in situ hybridization probe (top) and anti-Crz (middle) at 1.5 hours APF. The hybridization signals are indicated by arrowheads or by a circle. (H) rpr promoter activity in vCrz neurons at 1 hour APF. Crz-IRy (top), rpr-gal4-driven GFP expression (middle) and merge of the two (bottom). A vCrz neuron positive for both GFP and Crz-IRy appears in yellow. (I) Rpr-gal4-mediated p35 expression (rpr-gal4/UAS-p35) suppresses the death of ~10 vCrz neurons (brackets) at 7-9 hours APF. Two different specimens are shown here. Scale bars: in D, 50 μm for A-D,I; in E, 50 μm for E,F; 10 μm in G,H.

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Genetic reduction of diap1 levels in half also did not accelerate death of vCrz neurons, as mutants heterozygous for th4 or Df(3L)brm11 alleles showed normally scheduled death of vCrz neurons (data not shown), although these alleles dominantly exacerbate rpr-induced death of eyes (e.g. Lisi et al., 2000). These overall results support that RPR-mediated caspase activation does not involve the role of RPR as a DIAP1 antagonist.

As the pro-apoptotic action of RPR can be nullified by DIAP1 (e.g. Lisi et al., 2000), we tested whether gain-of-diap1 functions can suppress vCrz PCD. This was accomplished in two ways: one is th4 allele that was shown to suppress rpr-induced photoreceptor cell death (Lisi et al., 2000); the other is from transgenic diap1 expression in Crz neurons (Crz-gal4/UAS-diap1). Surprisingly, neither th4 nor ectopic diap1 expression suppressed vCrz PCD (Fig. 7D,E). Similar results were obtained from ectopic diap2 expression (data not shown). The negative results from ectopic diap1 expression is unlikely to be due to the lack of active DIAP1, as the same transgenic construct rescued the PCD of salivary glands (Fig. 7F).
As the apical caspase DRONC is a primary target of DIAP1 (Meier et al., 2000; Muro et al., 2002; Wilson et al., 2002), the lack of DIAP1 function may suggest that DRONC is not responsible for vCrz death. Contrary to this prediction, vCrz PCD was significantly delayed in dronc-null mutants (dronc51/droncI29) (Chew et al., 2004; Xu et al., 2005). Approximately 12 neurons still survived at 7 hours APF, while the number was reduced to ~8 at 16 hours APF (Fig. 7G), and none at 48 hours APF (data not shown). Comparable delay of the death was observed in another dronc-null mutant (droncS1/droncS2) (data not shown), suggesting that DRONC is a caspase that executes vCrz-cell death. However, the delay of death in the absence of DRONC indicates that activities from other caspases are also required for timely execution of vCrz PCD.

Activation of DRONC may require the adaptor protein DARK, a fly homolog of vertebrate Apaf1 (Rodriguez et al., 1999). If so, then lack of DARK may phenocopy dronc-null mutants. Remarkably, Crz-IR patterns in a homozygous dark-null mutant (darkCD9) were comparable with those of dronc mutants (compare Fig. 7H with 7G). These data suggest that an apoptosome consisting of DRONC and DARK is an essential component for vCrz PCD.

**DISCUSSION**

During post-embryonic CNS development in *Drosophila*, two prominent waves of neuronal cell death have been observed mostly in the VNC: the first during prepupal stage; and the second within prominent waves of neuronal cell death have been observed mostly comparable with those of vCrz death. Contradictory to this prediction, vCrz PCD was significantly delayed in DIAP1 function may suggest that DRONC is not responsible for (Meier et al., 2000; Muro et al., 2002; Wilson et al., 2002), the lack of DARK may phenocopy fly homolog of vertebrate Apaf1 (Rodriguez et al., 1999). If so, then lack of DARK may phenocopy dronc-null mutants. Remarkably, Crz-IR patterns in a homozygous dark-null mutant (darkCD9) were comparable with those of dronc mutants (compare Fig. 7H with 7G). These data suggest that an apoptosome consisting of DRONC and DARK is an essential component for vCrz PCD.

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mediated signal transduction probably controls remodeling of persistent neurons, as well as PCD of obsolete neurons during this crucial developmental period. These observations then raise the important issue of how distinct neuronal fates (remodeling versus death) are determined in response to the same hormonal stimulus and receptor types involved. Perhaps activated EcR-B in persistent neurons might silence the death pathway or turn on anti-apoptotic activities.

**Apoptotic pathways downstream of activated EcR**

In the case of ecysyne-triggered salivary gland and midgut degeneration, northern blotting has shown that rpr and hid are transcriptionally induced just prior to death (Jiang et al., 1997; Jiang et al., 2000). Such induction requires BR-C functions, as rpr and hid expression in these tissues is impaired by rhp5 and 2Bc2 mutant alleles of the BR-C locus (Jiang et al., 2000; Lee et al., 2002). Ecysyne also directly activates rpr transcription in the salivary glands via an interaction between activated EcR and its consensus binding sequence (EcRE) within 1.3 kb upstream of the rpr (Jiang et al., 2000). Our various findings support rpr as an intracellular death promoter for vCrz PCD. Although we do not have definitive evidence for direct activation of rpr by ecysyne, as the 1.3 kb rpr promoter apparently drives p35 expression in vCrz neurons (Fig. 61), we favor the hypothesis that activated EcR-B directly induces rpr transcription in the doomed vCrz neurons. Uregulation of rpr, however, does not seem to require BR-C, as we found normal vCrz PCD in the BR-C mutants (data not shown).

Another downstream target of the ecysyne signaling is DRONC. In vitro treatment of salivary glands and midgut with ecysyne induces dronc expression (Dorstyn et al., 1999), perhaps through a direct interaction between activated EcR-B1 and a consensus EcRE found in the dronc promoter (Cakouros et al., 2002; Cakouros et al., 2004). Uregulation of dronc transcription may be important for supplying doomed cells with a sufficient amount of DRONC in order to conduct massive cellular destruction in response to death signals. Further analysis will be necessary to determine if this also occurs in doomed vCrz neurons.

Involvement of RPR and caspases in the vCrz PCD raises another fundamental issue of how RPR leads to caspase activation. According to a current model, interactions between RPR and DIAP1 antagonize the inhibitory action of DIAP1, resulting in the accumulation of free active caspases (reviewed by Bergmann et al., 2003). By contrast, we did not find any evidence for DIAP1 as a survival factor for vCrz neurons. Although other DIAP1-like proteins in Drosophila (DIAP2, BRUCE and DETERIN) are possibly functional in this system, we speculate that this might not be the case. This is because failure of ectopic diap1 expression to block vCrz PCD suggests that other DIAP family members would not be effective in inhibiting vCrz-cell death, as anti-apoptotic functions of these proteins are mediated by consensus BIR domains (Bergmann et al., 2003). Thus, we propose that RPR-mediated caspase activation occurs independently of DIAP1 in vCrz neurons.

RPR perhaps mediates an assembly of the apoptosome, as both DRONC and DARK — two essential components of the apoptosome — are necessary for vCrz PCD (Fig. 7G,H). In vertebrate cells, the formation of the apoptosome triggered by the release of cytochrome C (cycC) from mitochondria is an essential step towards caspase activation (Liu et al., 1996; Cain et al., 1999). Although such molecular events are not evident in flies yet, a recent report showed that cycC-d is able to activate caspases during spermatogenesis (Arama et al., 2006). In this regard, it will be interesting to determine roles of cycC as an upstream regulator for caspase activation for vCrz PCD.

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