Presumptive TRP channel CED-11 promotes cell volume decrease and facilitates degradation of apoptotic cells in Caenorhabditis elegans.
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Apoptotic cells undergo a series of morphological changes. These changes are dependent on caspase cleavage of downstream targets, but which targets are significant and how they facilitate the death process are not well understood. In Caenorhabditis elegans an increase in the refractivity of the dying cell is a hallmark morphological change that is caspase dependent. We identify a presumptive transient receptor potential (TRP) cation channel, CED-11, that acts in the dying cell to promote the increase in apoptotic cell refractivity. CED-11 is required for multiple other morphological changes during apoptosis, including an increase in electron density as visualized by electron microscopy and a decrease in cell volume. In ced-11 mutants, the degradation of apoptotic cells is delayed. Mutation of ced-11 does not cause an increase in cell survival but can enhance cell survival in other cell-death mutants, indicating that ced-11 facilitates the death process. In short, ced-11 acts downstream of caspase activation to promote the shrinkage, death, and degradation of apoptotic cells.

TRP channel | apoptosis | C. elegans | cell volume | apoptotic volume decrease

Apoptosis, also referred to as “programmed cell death,” is defined by a set of morphological and biochemical changes in the dying cell (1, 2). These changes both reflect the death of the cell and prepare the cell for engulfment and degradation by phagocytes. Ineffective execution of apoptosis can lead to incomplete cellular degradation or to the survival of unwanted cells, events associated with diseases such as autoimmune disorders and cancer (3, 4). Both the death process and morphological changes that occur during apoptosis are initiated by cysteine proteases known as “caspases” (5, 6). Although proteomic studies have identified hundreds of proteins cleaved by caspases during apoptosis, many questions remain about how these proteins function during apoptosis and their contributions to the death process.

Cell shrinkage is a characteristic morphological change during apoptosis and has been used to differentiate apoptosis from necrosis, but the molecular mechanism and significance of apoptotic cell shrinkage are unclear (7). It has been hypothesized that cell shrinkage during apoptosis, termed “apoptotic volume decrease” (AVD), could occur through a mechanism similar to that of the regulatory volume decrease (RVD) most cells undergo when returning to a baseline volume after hypoosmotic-induced cell swelling (8). During RVD, potassium and chloride channels are activated, resulting in an efflux of potassium and chloride from the cell, followed by an efflux of water driven by the osmotic gradient (9).

In Caenorhabditis elegans, an increase in cell refractivity as observed by Nomarski differential interference contrast (DIC) microscopy is one of the defining apoptotic morphological changes (10). The increase in the refractivity of apoptotic cells is dependent on the CED-3 caspase (11). Many mutants have been identified in which refractile apoptotic cells persist unengulfed (12). From a screen for mutants that alter the accumulation of refractile apoptotic cells of a ced-5 engulfment mutant, we discovered a gene, ced-11, that is required for the refractile appearance of apoptotic cells. ced-11 encodes a presumptive transient receptor potential (TRP) channel. TRP channels are nonselective cation channels that participate in diverse sensory processes and can be involved in regulating RVD (13, 14). Like most TRP channels, the CED-11 protein can localize to the plasma membrane. We found that CED-11 is required for cell shrinkage, suggesting that it, along with other TRP family members, might have a mechanistically conserved role in cell volume regulation. We conclude that CED-11 acts in the dying cell directly or indirectly downstream of CED-3 activation to promote AVD and that without this change in volume apoptotic cells take longer to degrade and have an increased chance of survival.

Results

ced-11 Is Required for the Highly Refractile Morphology of Apoptotic Cells. C. elegans apoptotic cells acquire a raised, highly refractile appearance when visualized by DIC microscopy (Fig. 1A) (10). We identified the gene ced-11 (cell death-11) in a screen for suppressors of the accumulation of refractile apoptotic cells that occurs in ced-5 mutants, which are defective in the engulfment of apoptotic cells (Fig. 1 B–D). ced-11; ced-5 mutants lack refractile apoptotic cells and instead contain flat disk-like cells that are distinct from living cells and that we hypothesized were nonrefractile apoptotic cells. We confirmed that the flat disk-like cells observed in ced-11 animals are cells that normally undergo apoptosis: null alleles of ced-3 and ced-4, which prevent apoptotic cell deaths, prevented the appearance of the flat disk-like cells in ced-11; ced-3 and ced-4 ced-11

Significance

Apoptosis is required for normal animal development and homoeostasis. Apoptosis is driven by caspases, cysteine proteases that cleave downstream targets and cause cell death and degradation. A classic hallmark of apoptosis is cell shrinkage. We identify a presumptive transient receptor potential (TRP) family cation channel, CED-11, that acts during apoptosis in Caenorhabditis elegans downstream of CED-3 caspase activation to promote a decrease in cell volume and facilitate the death and degradation of apoptotic cells. TRP channels can stimulate cell shrinkage in response to osmotic stress. Our results suggest that the mechanism of cell shrinkage during apoptosis might be similar to the regulatory volume decrease (RVD) that cells undergo after the cell swelling induced by hypoosmotic stress.

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Apoptotic cells have an altered ultrastructure. To understand how changes in refractivity correlate with other hallmarks of apoptosis, we examined the ultrastructure of apoptotic cells as visualized using EM in wild-type and ced-11 mutant embryos. Previous EM studies of C. elegans revealed that after engulfment apoptotic cells progressively lose the integrity of their nuclei (19). Apoptotic cells with intact nuclei stain darkly compared with surrounding nonapoptotic cells and have a condensed cytoplasm and compact chromatin; we refer to such cells as “prebreakdown corpses.” Apoptotic cells that do not have intact nuclei have cytoplasm that is lighter than surrounding nonapoptotic cells and contain small dark-staining fragments likely to be remnants of apoptotic cell refractility (n = 4). We conclude that CED-11 acts cell autonomously to increase refractility during apoptosis.

**Table 1. ced-11 nonrefractile apoptotic cells are cells that normally undergo apoptosis**

<table>
<thead>
<tr>
<th>Genotype</th>
<th>No. refractile apoptotic cells</th>
<th>No. nonrefractile apoptotic cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5-fold-stage embryos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wild-type</td>
<td>12.0 ± 1.8</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>ced-11(n2744)</td>
<td>0.0 ± 0.0</td>
<td>4.8 ± 0.9</td>
</tr>
<tr>
<td>ced-3(n717)</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>ced-11(n2744);</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ced-3(n717)</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>ced-4(n1162)</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>ced-4(n1162)</td>
<td>0.0 ± 0.0</td>
<td>0.0 ± 0.0</td>
</tr>
<tr>
<td>ced-11(n2744)*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Threefold-stage embryos</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ced-5(n1812)</td>
<td>27.6 ± 3.1</td>
<td>1.1 ± 1.1</td>
</tr>
<tr>
<td>ced-11(n2744);</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ced-5(n1812)</td>
<td>1.0 ± 1.1</td>
<td>24.3 ± 4.3</td>
</tr>
<tr>
<td>ced-5(n1812)</td>
<td>0.3 ± 0.4</td>
<td>0.1 ± 0.3</td>
</tr>
<tr>
<td>ced-3(n717)</td>
<td>0.6 ± 0.8</td>
<td>0.5 ± 0.8</td>
</tr>
<tr>
<td>ced-11(n2744);</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ced-5(n1812)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ced-3(n717)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Apoptotic cells were identified by DIC. Data are shown as mean ± SD; n > 20. *Strains contain dpy-17(e164).
membranes and chromatin; we refer to such cells as “postbreakdown corpses” (19, 20). Dark staining as visualized in EM is caused by the binding of electron-dense dyes to lipids and proteins, and it has been proposed that the increased electron density of prebreakdown apoptotic cells results from an increase in the concentration of macromolecules (21).

We considered cells that appeared to be engulfed to be apoptotic. As reported by Robertson and Thomas (19), in wild-type embryos prebreakdown apoptotic cells stained darker than living cells, with a shrunken cytoplasm, bloated organelles, and condensed chromatin (Fig. 2 A and B). By contrast, in ced-11 embryos prebreakdown apoptotic cells did not stain darkly and generally looked similar to living cells, although they were still rounded and displayed some apoptotic cell features, including chromatin condensation and organelle bloating (Fig. 2 B and C and Fig. S3 C–E). We observed the absence of dark staining in the prebreakdown apoptotic cells of ced-11 embryos in embryos of different ages, including before the bean-comma stage and after the 1.5-fold stage (Fig. S3 A–D). We conclude that ced-11 is required for an increase in electron-dense staining during apoptosis.

Also, as reported by Robertson and Thomas (19), the postbreakdown corpses of wild-type embryos contained membranous whorls and remnants of chromatin, and the cytoplasm did not stain darkly (Fig. 2 D and Fig. S4 A). The postbreakdown corpses of ced-11 animals looked similar to those of the wild type, indicating that apoptotic cells in ced-11 animals reach late stages of degradation (Fig. 2 E and F and Fig. S4 B and C).

In addition to the reduction in electron-dense staining, ced-11 prebreakdown apoptotic cells appeared to differ in nuclear architecture. Prebreakdown apoptotic cells in wild-type embryos often had wrinkled nuclei (40%) and separation between the nucleus and cytoplasm (60%), although nuclear pore junctions could still be seen (Fig. 2G). Nuclear wrinkling and separation of the nucleus and cytoplasm might reflect altered structural integrity of the nuclear membrane. By contrast, prebreakdown apoptotic cells in ced-11 embryos did not have wrinkled nuclei and showed nuclear–cytoplasm separation less frequently (about 15%) (Fig. 2G).

Engulfment Is Normal in ced-11 Mutants. Next we asked if ced-11 apoptotic cells could be recognized and engulfed normally. We used time-lapse videos of embryos expressing a Pced-1::ced-1::GFP translational fusion to monitor the engulfment of three cells (C1, C2, and C3) that die during ventral enclosure of the embryo, when the epidermal sheets meet at the ventral midline (Fig. 3 A–D) (22). CED-1 is a transmembrane receptor that is expressed in engulfing cells and that clusters around apoptotic cells and mediates their engulfment (23). We observed that C1, C2, and C3 were engulfed during ventral enclosure in both wild-type and ced-11 mutant embryos, indicating that both the onset of apoptosis and engulfment are grossly normal (Fig. 3 A and B). In addition, engulfment took a normal length of time in ced-11 mutant embryos (~6 min), and CED-1::GFP was removed from the phagosomes at a normal rate, showing that both engulfment and the beginning of the phagosome maturation process are normal (Fig. 3E). We conclude that ced-11 is required for the highly refractile morphology of apoptotic cells but is not required for the onset of apoptosis or for engulfment.

ced-11 Apoptotic Cells Are Larger. We noticed that apoptotic cells in ced-11 embryos look larger than apoptotic cells in wild-type embryos. To quantify this difference, we measured the sizes of apoptotic cell-containing phagosomes at the time of engulfment, using the time-lapse movies of CED-1::GFP that we used to determine that engulfment is normal in ced-11 mutants. Newly engulfed apoptotic cells in ced-11 embryos were larger than apoptotic cells in wild-type embryos, with an average diameter of 2.7 μm vs. 2.3 μm (Fig. 4A). In addition, we measured the size of the apoptotic cells 2 min after engulfment and found that the ced-11 apoptotic cells shrank by an average of 0.2 μm, whereas the ced-11 apoptotic cells were unchanged in size (Fig. 4B). Thus, ced-11 is required for apoptotic cell shrinkage. Apoptotic cells are generally spherical, so the 15% reduction in diameter at the time of engulfment corresponds to a 38% reduction in volume.

ced-11 Apoptotic Cells Are Delayed in Degradation. Because ced-11 apoptotic cells have defects in cell shrinkage and look similar to living cells by EM, we tested whether apoptotic cells in ced-11 embryos take longer to degrade. Engulfed apoptotic cells are degraded inside phagosomes. RAB-7 is recruited to apoptotic cell-containing phagosomes shortly after engulfment and persists on the phagosomes until cell-corpse degradation is complete (24). We used the disappearance of GFP::RAB-7 to assess cell-corpse degradation. We found that the cells in ced-11 embryos took longer to degrade (60 min) than did wild-type apoptotic cells (45 min) (Fig. 4 C and D). In addition, we counted the number of GFP::RAB-7 phagosomes in fourfold embryos and found the average number of such phagosomes was greater in the ced-11 embryos (10 phagosomes) than in the wild type (five phagosomes), as is consistent with the delay in degradation (Fig. 4E). We conclude that ced-11 promotes the degradation of apoptotic cells.

ced-11 Mutants Do Not Have Extra Surviving Cells, but ced-11 Mutation Can Enhance the Antiapoptotic Effects of Other Cell-Death Mutations. Does CED-11 promote the deaths of apoptotic cells?
Using DIC, we noted that fewer apoptotic cells were observed in ced-11 embryos than in the wild type (Table 1 and Fig. S5), suggesting that cell-death execution might be affected. We examined cell death in ced-11 animals using two assays. First, we measured the survival of 16 pharyngeal cells that normally die during embryogenesis. Second, we measured the survival of five of seven cells (P2.aap and P9–12.aap) in the ventral nerve cord that normally die in late L1/early L2 larvae (25). We found no extra surviving cells in ced-11 mutant animals with either assay (Fig. 5 A and B and Fig. S6). Because there was no extra cell survival in ced-11 mutant animals, we propose that the apparent difference in apoptotic cell number results from the difficulty in distinguishing some ced-11 nonrefractile apoptotic cells from living cells when using DIC.

We postulated that perhaps, even if ced-11 promotes the deaths of apoptotic cells, if ced-11 mutant cells are engulfed normally, they will not survive. C. elegans genes involved in engulfment have a weak effect on the cell-death killing process: In engulfment mutants, an average of 0.3–1.2 extra cells survive in the ventral nerve cord, as opposed to an average of 4.9 extra cells in mutants defective in the ced-3 caspase gene (26). Therefore, we assayed cell death in double mutants defective in both ced-11 and the engulfment process. We found that ced-11 mutation enhances the ventral cord cell-death defect caused by mutations in the engulfment genes ced-1, ced-2, ced-5, ced-6, ced-10, and ced-12, nearly doubling the average number of surviving extra cells (Fig. 5B and Fig. S6). A ced-11 mutation did not enhance the cell-death defect of ced-7 mutants (Fig. 5B). ced-7 is distinct from the other engulfment genes in other ways: ced-7 is the only engulfment gene known to be required to act in the dying as well as in the engulfing cell, and ced-7 mutants have a much stronger cell-death defect than the other engulfment mutants. We suggest that ced-7 functions in the apoptotic cell to promote cell death, possibly in the same pathway as ced-11.

In addition, we analyzed the ability of ced-11 mutations to enhance weak mutant alleles of the cell-death execution genes ced-3 and ced-4 and of a mutation in a gene that encodes a caspase target, ced-8 (11, 15, 27). Mutation of ced-11 enhanced cell survival caused by a mutation in the execution gene ced-4 but
did not enhance alleles of ced-3 or ced-8 (Fig. 5B and Fig. S6). ced-4 has a proapoptotic isoform, ced-4S, which acts in the execution pathway with ced-3, and an antiapoptotic isoform, ced-4L, the function of which is less well understood. Perhaps ced-4L acts in parallel to ced-11 to regulate cell death and ced-4S, ced-3, and ced-8 act in the same pathway as ced-11. In any case, these data indicate that ced-11 can facilitate cell killing.

**Discussion**

ced-11 is required for many but not all of the cellular changes that occur during apoptosis: shrinkage, increased refractility, increased electron density, and nuclear membrane wrinkling and separation, but not chromatin condensation, plasma membrane rounding, or engulfment. ced-11 encodes a presumptive TRP channel based on sequence similarity to known TRP channels (17). Like most TRP channels, the CED-11 protein can localize to the plasma membrane as well as to internal membranes (16). ced-11 acts downstream of ced-3, because ced-3 is required for the initiation of cell death and ced-11 is required for a subset of ced-3-dependent changes that contribute to cell death. That ced-11 mutation does not enhance the cell-death defect of weak ced-3 mutation strongly suggests that ced-11 and ced-3 act in the same pathway rather than in parallel to promote cell death. That ced-11 mutation enhances cell survival in engulfment-mutant strains and results in defects in apoptotic cell degradation suggests that cellular changes driven by ced-11 contribute to the process of cell death and cell degradation. Taken together, our data show that ced-11 acts downstream of ced-3 and in parallel to phagosome maturation to promote the death and degradation of the apoptotic cell (Fig. 6A). We propose that the delay in degradation in ced-11 animals is caused by the defect in cell-volume reduction and that this degradation defect can be bypassed by the phagocytic pathway, although more slowly. If the dying cell is not engulfed and degraded by a phagosome, it has a greater chance of survival.

ced-11 is required for the reduction of cell volume during apoptosis. As noted above, cell shrinkage during apoptosis has been called “apoptotic volume decrease” (AVD) to differentiate it from RVD induced by osmotic challenge (8). AVD occurs in normotonic cellular conditions and has been proposed to be induced by the opening of potassium and chloride channels in the plasma membrane, causing an efflux of potassium and chloride ions followed by water (28–30). The mechanism for activating such channels during apoptosis is unknown. Multiple TRP channels have been implicated in cell-volume regulation (9, 31, 32). TRPV4 mediates a Ca2+ influx in response to hypoxosmotic stress and had been hypothesized to stimulate calcium-activated potassium and chloride channels, resulting in RVD (32, 33). We propose that CED-11 contributes to AVD by a similar mechanism.

Apoptotic cells in ced-11 animals fail to increase in refractility. The highly refractile appearance of apoptotic cells in C. elegans is the defining morphological feature used to differentiate living cells from dying cells, but the biological cause of the refractility is unknown. Refractility is known to increase with increased concentrations of proteins and other macromolecules but shows little or no change in response to changes in salt concentration, changes in pH, denaturation of proteins, or digestion of proteins to amino acids (34). The refractility of mammalian cells also increases during apoptosis, and it has been suggested that this increase reflects a decrease in intracellular water and a corresponding increase in the concentration of proteins and other macromolecules in the cell (35). The increased refractility of apoptotic cells observed in C. elegans could also result from an increase in the concentration of macromolecules. This hypothesis is supported by our observation that apoptotic cells in ced-11 embryos do not stain darkly in EM. Electron-dense staining in EM reflects high concentrations of proteins and lipids (7). Furthermore, EM studies of mammalian cells in a hypoosmotic solution that induced cell shrinkage showed an increased electron density compared with cells in an iso-osmotic solution (36).

Fig. 5. Mutation of ced-11 does not cause cell survival on its own but can enhance cell survival in other cell-death mutants. (A) Average number of extra cells present in the anterior pharynx of L3–L4 hermaphrodites. Data are shown as mean ± SD; n > 20. (B) Average number of extra cells in the ventral cords of L4 hermaphrodites. Error bars indicate SEM; n > 100. All strains contain n1816. The ced-11 allele used was ced-11(n2744). The dagger indicates the presence of dpy-18. **p < 0.001, one-way ANOVA with Sidak’s multiple comparisons test.

**Fig. 6. Model for CED-11 function in apoptosis.** CED-11 acts downstream of CED-3 to promote cell-autonomous death and degradation in parallel with engulfment and phagosome-mediated degradation. CED-11 is directly or indirectly activated by the CED-3 caspase. CED-11 activation results in a decrease in cell volume, driving an increase in macromolecule density and leading to the observed increases in cellular refractility and electron density. CED-11–mediated changes in the apoptotic cell promote its death and degradation. (A) Pathway. (B) Schematic.

**Table 1.** Extra Cells in the Anterior Pharynx

<table>
<thead>
<tr>
<th>Genotype</th>
<th>No. extra cells</th>
<th>Range extra cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild-type</td>
<td>0.04 ± 0.03</td>
<td>0–1</td>
</tr>
<tr>
<td>ced-3(n177)</td>
<td>13.2 ± 1.9</td>
<td>10–16</td>
</tr>
<tr>
<td>ced-11(n2744)</td>
<td>0.09 ± 0.06</td>
<td>0–1</td>
</tr>
<tr>
<td>ced-11(n2466)</td>
<td>0.0 ± 0.00</td>
<td>0</td>
</tr>
</tbody>
</table>

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We propose that CED-11 functions as a TRP channel to alter ion flow and promote a cell volume decrease through a loss of intracellular water that causes an increased concentration of proteins and other macromolecules, resulting in the observed increase in cellular refractivity and electron density (Fig. 6B). More specifically, we hypothesize that activation of CED-11 in apoptotic cells causes an influx of Ca^{2+}, which activates Ca^{2+}-activated K^+ and Cl^- channels in the cell and leads to an efflux of K^+ down the concentration gradient and an efflux of Cl^- to maintain electro-neutrality, followed by an efflux of water down the osmotic gradient. Consequently, cell volume is reduced, and an increase in the concentration of macromolecules in the cell results in the increase in refractivity and electron density. The reduction of cell volume might also contribute to the observed changes in nuclear membrane structure. In conclusion, we find that a presumptive TRP channel acts downstream of caspase activation to promote cell shrinkage and contributes to apoptotic cell degradation in parallel to the phagosome degradation pathway.

Materials and Methods
A more complete description is available in SI Materials and Methods.