Bax Deletion Further Orders the Cell Death Pathway in Cerebellar Granule Cells and Suggests a Caspase-independent Pathway to Cell Death


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Abstract. Dissociated cerebellar granule cells maintained in medium containing 25 mM potassium undergo an apoptotic death when switched to medium with 5 mM potassium. Granule cells from mice in which Bax, a proapoptotic Bcl-2 family member, had been deleted, did not undergo apoptosis in 5 mM potassium, yet did undergo an excitotoxic cell death in response to stimulation with 30 or 100 μM NMDA. Within 2 h after switching to 5 mM K⁺, both wild-type and Bax-deficient granule cells decreased glucose uptake to <20% of control. Protein synthesis also decreased rapidly in both wild-type and Bax-deficient granule cells to 50% of control within 12 h after switching to 5 mM potassium. Both wild-type and Bax −/− neurons increased mRNA levels of c-jun, and caspase 3 (CPP32) and increased phosphorylation of the transactivation domain of c-Jun after K⁺ deprivation. Wild-type granule cells in 5 mM K⁺ increased cleavage of DEVD-aminomethylcoumarin (DEVD-AMC), a fluorogenic substrate for caspases 2, 3, and 7; in contrast, Bax-deficient granule cells did not cleave DEVD-AMC. These results place BAX downstream of metabolic changes, changes in mRNA levels, and increased phosphorylation of c-Jun, yet upstream of the activation of caspases and indicate that BAX is required for apoptotic, but not excitotoxic, cell death. In wild-type cells, Boc-Asp-FMK and ZVAD-FMK, general inhibitors of caspases, blocked cleavage of DEVD-AMC and blocked the increase in TdT-mediated dUTP nick end labeling (TUNEL) positivity. However, these inhibitors had only a marginal effect on preventing cell death, suggesting a caspase-independent death pathway downstream of BAX in cerebellar granule cells.

Extensive cell death is an important part of the development and ongoing maintenance of tissues in multicellular organisms (Glucksman, 1951; Clarke and Clarke, 1996). The demise of many cells is modulated by members of the BCL-2 family of proteins (Korsmeyer, 1996; White, 1996). BCL-2 was first recognized as a modulator of cell death in studies of follicular B cell lymphoma in which overexpression of BCL-2 promotes transformation by rendering cells more resistant to apoptosis. The antiapoptotic activity of BCL-2 has been borne out in numerous cell types in response to a variety of stimuli (for review see Korsmeyer, 1996; White, 1996).

Several homologues of BCL-2 have been isolated, including some members of this family that are antiapoptotic, like BCL-2, and others that are proapoptotic (for review see Korsmeyer, 1996; White, 1996). BCL-2 family members that inhibit apoptosis include CED-9, MCL-1, A1, and E1B-19K. Family members that promote apoptosis include BAX, BAK, and BAD. BCL-X, another BCL-2 homologue, has both an antiapoptotic, long-splice variant, BCL-XL, and a proapoptotic, short-splice variant, BCL-XS. While the essential biochemical function of BCL-2 family members remains under investigation, their activity is regulated, in part, by dimerization among the various family members (Korsmeyer, 1996; Oltvai et al., 1993). In this rheostat model, the ratio of proapoptotic versus antiapoptotic molecules determines the fate of a cell. Dimerization among family members is mediated by three highly conserved domains, BH1, BH2, and BH3. BH1 and BH2 appear critical for antiapoptotic members (BCL-2 and BCL-XL) to heterodimerize with the proapoptotic BCL-2 family member, BAX (Yin et al., 1994), while the BH3 domain of...
BAX is essential for its heterodimerization and activity (Chittenden et al., 1995).

Studies of mice deficient in BCL-X or BAX have highlighted these two family members as particularly important for the nervous system. Apoptosis in developing sensory and central nervous system neurons is greatly increased in mice deficient in Bcl-X (Motoyama et al., 1995). Dissociated sympathetic neurons from Bax-deficient animals are remarkably resistant to trophic factor deprivation–induced death, and motor neurons from the facial nucleus do not degenerate in response to axotomy (Deckwerth et al., 1996). In contrast, isolated thymocytes from Bax-deficient mice are not resistant to apoptosis (Knudson et al., 1995). In this study, we determined whether BAX was critical for cerebellar granule cell apoptosis.

Dissociated cerebellar granule cells from early postnatal rats can be maintained in serum-containing medium by elevating extracellular potassium levels (25 mM) (Gallop et al., 1987), or by adding low concentrations of N-methyl-α-aspartic acid (NMDA) to the culture medium (Balazs et al., 1988). Both low concentrations of NMDA and depolarization are presumed to mimic endogenous excitatory activity (Burgoyne et al., 1993); the survival promotion is mediated by increases in intracellular calcium (Gallop et al., 1987). Overstimulation of glutamate receptors on granule cells leads to an excitotoxic death (Schramm et al., 1995; Dessi et al., 1993; Lafon-Cazal et al., 1993). Dissociated cerebellar granule cells develop characteristics of mature cerebellar granule cells in vivo including an extensive neuritic network, expression of excitatory amino acid receptors, and production and release of l-glutamate (Burgoyne et al., 1993). Removal of both potassium and serum from dissociated cerebellar granule cells triggers a cell death that is morphologically apoptotic, accompanied by DNA fragmentation, and dependent on macromolecular synthesis (D’Mello et al., 1993; Nardi et al., 1997). This apoptotic cell death presumably mimics the naturally occurring death of 20–30% of granule cells (Caddy and Biscoe, 1979), which is important for matching the number of granule cells with Purkinje cells, that occur during the third through fifth postnatal weeks (Wets and Herrup, 1983; Williams and Herrup, 1988).

In the current study, we demonstrate that BAX is required for programmed cell death (PCD), but not excitotoxic cell death, of cerebellar granule cells. We used this homogeneous population of BAX-dependent neurons to assess when BAX was acting in the program that commits a cell to die. We found that while Bax-deficient granule cells did not die, they did progress through several early changes associated with neuronal PCD (Deckwerth and Herrup, 1993; Estus et al., 1994; Freeman et al., 1994; Miller and Johnson, 1996) including decreases in protein synthesis and glucose uptake, and an increase in the mRNA level of the AP-1 transcription factor c-jun. In contrast to these events that do occur in both Bax+/- and Bax−/− cells, we found that Bax−/− lysates did not cleave Ac-DEVD-aminomethylcoumarin (DEVD-AMC), a fluorogenic substrate for caspases 2, 3, and 7 that was cleaved by lysates from wild-type cells undergoing apoptosis. These results identify a central nervous system cell type that requires BAX to undergo PCD and clearly place BAX downstream of changes in glucose uptake, protein synthesis, and certain mRNA levels and upstream of the activation of a DEVD-selective caspase. We further investigated the role of the caspases in PCD of granule cells by using peptide inhibitors of caspases. Although these compounds blocked cleavage of DEVD-AMC completely and blocked the increase in TdT-mediated dUTP nick end labeling (TUNEL)–positivity, they only had a marginal effect on cell survival, suggesting the presence of caspase-independent cell death effectors downstream of BAX.

Materials and Methods

Breeding and Genotyping of Mice with Different Gene Dosages of Bax

Mice heterozygous for Bax (Knudson et al., 1995) were mated to yield F1 offspring with Bax−/−, Bax+/-, and wild-type genotypes. At postnatal day 4–5, tail DNA was prepared and screened by PCR as described (Deckwerth et al., 1996).

Cell Culture Media

All cell media were based on Basal Medium Eagle (Life Technologies, Grand Island, NY) containing 100 U/ml penicillin and 100 μg/ml streptomycin. The following additions were made: K5+S medium, 10% dialyzed FBS 10,000 mol wt cutoff (Sigma Chemical Co., St. Louis MO); K25+S medium, 10% dialyzed FBS, 20 mM KCl, K25−S medium, 20 mM KCl; K5−S medium, no additions. Dialyzed serum was used because adding fresh medium containing nondialyzed serum to cerebellar granule cells is toxic. This sensitivity to nondialyzed serum develops after several days in culture because of the glutamate in the serum (Schramm et al., 1990).

Neuronal Culture

This cell culture protocol is a modification of previous protocols (Levi et al., 1984) and is extensively detailed in Miller and Johnson (1996). The only difference was that cerebella from postnatal day seven (P7) mice, sliced into 1-mm pieces, and incubated at 37°C for 15 min in 0.30 mg/ml trypsin (Worthington Biochemical Corp., Freehold, NJ). The tissue was then triturated in K25+S medium with 0.5 mg/ml trypsin inhibitor (Sigma Chemical Co.) by using a flame-polished Pasteur pipette. The resulting cell suspension was spun at 500 g for 6 min. The pellet was gently triturated in fresh K25+S medium and filtered through a nitex filter (size 3-20/14; Tetko Inc., Elmsford, NY). Trypan blue exclusion was used to determine the number of the living neurons before plating. 2–2.5 × 10⁵ cells/cm² in either four-well (Nunc, Naperville, IL) or 35-mm dishes (Corning Inc., Corning, NY). Before plating, dishes were coated with 0.1 mg/ml poly-l-lysine (P2636; Sigma Chemical Co.). The granule cells were kept at 35°C in a humidified incubator with 5% CO₂, 95% air for 7 d. Fresh K25+S medium was added after 4 d in vitro. To reduce the number of nonneuronal cells, aphidicolin (3.3 μg/ml, Sigma Chemical Co.) was added to the medium 24–36 h after initial plating. The culture conditions do not support the survival of other neuronal cell types (Thangnipon et al., 1983; Kingsbury et al., 1985); the nonneuronal contamination was 1–2% (Miller and Johnson, 1996).

Treatment of Cultures

For studies of potassium deprivation, phosphatidylinositol-3 kinase (PI-3-K) inhibition, or inhibition of caspases, at 7 d in vitro, culture medium was replaced with either K5−S or K5+S medium after washing cells once with the respective medium. Control cultures were treated identically with K25+S medium. Special care was taken to assure that all media had been preincubated at 35°C, 5% CO₂, 95% air for 18–24 h. 30 μl M LY 294002 (Biomol Research Laboratories, Inc., Plymouth, PA) was added to K25+S medium to inhibit PI-3-K. Boc-aspartyl(OMe)-fluoromethylketo-
tone (BAF) and Z-VAD-fluoromethylketone were obtained from Enzyme Systems Products (Dublin, CA). For mammalian cell cultures, cells were treated at 10 d in vitro as described in Lafon-Cazal et al. (1993). Culture medium was removed and placed at 35°C, 5% CO\(_2\)/95% air. Culture medium was replaced with K5\(_2\)-free Locke's solution (154 mM NaCl, 5.6 mM KCl, 3.6 mM NaHCO\(_3\), 2.7 mM CaCl\(_2\), 5.6 mM d-glucose, 5 mM Hepes, pH 7.4) and then incubated at 35°C for 30 min in Mg\(^{2+}\)-free Locke's solution with 3\(\mu\)M Z-VAD-fmk (Sigma Chemical Co.) and 10, 30, or 100 \(\mu\)M NMMA (Sigma Chemical Co.), or 100 \(\mu\)M NMDA + 150 mM MK-801 (Research Biochemicals International, Natick, MA). Cells were washed twice for 15 min with Mg\(^{2+}\)-free Locke's solution at 35°C. The original culture medium was replaced and the cells were incubated at 35°C, 5% CO\(_2\)/95% air for 24 h after which cell viability was assessed.

**Determination of Cell Viability**

Cell viability was quantified from photomicrographs of representative fields of cells labeled with calcine AM (Molecular Probes Inc., Eugene, OR). Calcine AM is an acetoxyxymethyl ester fluoroscein derivative, which is cleaved and trapped inside viable cells that have nonspecific esterase activity (Bozyczko et al., 1993). The photomicrographs were both taken and scored by an observer naive to the experimental condition and to the genotype of the animal from which the culture was derived. Six photomicrographs at 200 magnification were taken for each condition and the number of calcine AM–positive cells was counted. This method of quantifying cell viability is detailed and validated in Miller and Johnson (1996).

**Metabolic Parameters**

Experiments were performed in four-well dishes (Nunc) with ~400,000 cells per well. After 7 d in vitro, culture medium was replaced with K5\(_5\)-S medium or K25\(_5\)-S medium (as described above). Detailed description of the following methods may be found in Deckwerth and Johnson (1993) and Miller and Johnson (1996).

**Rate of Protein Synthesis.** Neuronal cultures were labeled for 1 h at 35°C with 10 \(\mu\)Ci/ml of [\(\mu\)]^35S\]methionine (Radiochemical Centre, Amersham, UK). Culture medium was removed and placed at 35°C, 5% CO\(_2\)/95% air for 24 h after which cultures were washed three times with TBS (100 mM Tris, 0.9% NaCl, pH 7.6), blocked with 4% paraformaldehyde in PBS at 4°C, fixed with 4% paraformaldehyde in PBS at 4°C for 25 min, and washed three times with TBS (100 mM Tris, 0.9% NaCl, pH 7.6) and incubated in the dark at room temperature for the dark. Fluorescence was measured at excitation 360 nm and emission 460 nm in a fluorescence plate reader (Titertek Fluoroskan II; Flow Laboratories, Inc., McLean, VA). 20 min and 25 \(\mu\)l were both in the linear range of the assay with respect to time and amount of lystate added.

Although cultures were extensively washed before lysing cells, we were concerned that residual BAF or ZVAD from the culture medium might account for the block in DEVD-AMC cleavage in our enzyme assay. To test this possibility, we combined 8-h \(K^+\) deprivation lysates from BAF- or ZVAD-treated cultures with 8-h \(K^+\) deprivation lysates from untreated cultures and determined DEVD-AMC cleavage. We found that the 8-h lysates from the BAF- or ZVAD-treated cultures did not themselves contain any ability to inhibit the DEVD-AMC cleavage activity in our assay, demonstrating that the BAF and ZVAD in the culture medium had been adequately washed out before lysis (data not shown).

**Transfections of Cerebellar Granule Cells**

All constructs were under the cytomegalovirus (CMV) promoter, pGreen Lantern-1 (green fluorescent protein) was obtained from GIBCO BRL (Gaithersburg, MD). The BCI-2 construct is detailed in Greenlund et al. (1995a). The p35 construct was a generous gift from Dr. Lois K. Miller. pBlueScript I1 was used as control DNA (Short et al., 1988). Granule cells were transfected essentially as described in Xia et al. (1995b). In brief, after 5 d in vitro, cultures were switched to K25\(_5\)-S medium for 1 h after which DNA/CaCl\(_2\) precipitates were prepared as follows: An equal volume of DNA was added to precipitates were prepared as follows: An equal volume of DNA was added to DNA/CaCl\(_2\) precipitates were prepared as follows: An equal volume of DNA was added to

**RT-PCR**

Semiquantitative reverse transcription-PCR (RT-PCR) assays are based on those used for sympathetic neurons described in Freeman et al. (1994) and Estus et al. (1994), and extensively detailed by Estus (1997). Briefly, granule cells were swizada for K5\(_5\)-S medium for indicated times. Polyadenylated (poly-A) RNA was isolated from 400,000 cerebellar granule cells by using 35°C with 2.5 \(\mu\)g/ml of [\(\mu\)]^35S\]methionine (30 \(\mu\)Ci/ml; ICN Biomedicals, Inc., Irvine, CA) in K25\(_5\)-S or K5\(_5\)-S medium containing 500 \(\mu\)g/ml d-glucose. Cultures were washed three times, lysed, and added directly to liquid scintillation fluid and counted. Assays were linear with respect to time during the indicated measuring period (data not shown).

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**Phospho-Jun Staining**

Neuronal cultures were washed once with PBS, pH 7.4, before a 30-min fixation with 4% paraformaldehyde in PBS at 4°C. Neuronal cultures were washed three times with TBS (100 mM Tris, 0.9% NaCl, pH 7.6), blocked for 30 min in TBS containing 5% goat serum (Sigma Chemical Co.) and 0.3% Triton X-100 at room temperature, and incubated overnight at 4°C
with anti-phospho-c-Jun antibody (Ser 63; New England Biolabs Inc., Beverly, MA) diluted 1:200 in TBS containing 1% goat serum and 0.3% Triton X-100. Cultures were washed three times with TBS then incubated overnight at 4°C in a 1:400 dilution of 1.5 mg/ml Cy3-donkey anti-rabbit antibody (Jackson ImmunoResearch Laboratories, Inc., Westgove, PA) in the same buffer as the primary antibody. Cultures were washed twice with TBS, stained with 1 μg/ml bisbenzimide (Hoechst 33258; Molecular Probes Inc., Eugene, OR) for 20 min to visualize nuclei, then washed two additional times with TBS. The phospho-jun antibody does not react with the nonphosphorylated form of c-Jun and does not appreciably cross-react with the phosphorylated form of JunD or JunB (New England Biolabs Inc.).

**TUNEL Staining**

At 7 d in vitro, culture medium from cerebellar granule cells was replaced with either K5+S, K5+S plus 100 μM BAF, or fresh K25+S after washing the cells once with the appropriate medium. At 24 h after this treatment, cells were examined for DNA fragmentation using the In Situ Cell Death Detection Kit (Fluorescein; Boehringer Mannheim Biochemicals, Indianapolis, IN) according to the manufacturer’s instructions. In brief, cells were fixed for 30 min in 4% paraformaldehyde/PBS at room temperature, washed once with PBS, and permeabilized in 0.1% Triton X-100, 0.1% sodium citrate for 20 min at 4°C. After two more washes with PBS, the cells were incubated with 50 μl of the TUNEL reagent for 1 h at 37°C in the dark. Cells were then washed twice with PBS, stained with 1 μg/ml Hoechst 33258 (Molecular Probes Inc.), and washed twice more with PBS. The percentage of TUNEL-positive cells was calculated as the number of TUNEL-positive cells divided by the number of Hoechst-stained cells. For each condition, a naive observer counted two to five fields, each containing over 200 bisbenzimide-stained neurons. Results represent mean ± range for two independent experiments.

**Results**

**Bax −/− Neurons are Resistant to Apoptosis**

Disassociated cerebellar granule cells maintained in 25 mM K+ and serum undergo a PCD that is apoptotic if they are deprived of both potassium and serum (K5−S medium) (D’Mello et al., 1993). To determine whether BAX, a proapoptotic BCL-2 family member, was important in cerebellar granule cell apoptosis, we used cultures of dissociated cerebellar granule cells from P7 wild-type and Bax-deficient mice (Knudson et al., 1995). After 7 d in vitro, cultures of Bax +/+ and Bax −/− cerebellar granule cells were switched to medium containing low potassium and serum (K5+S) or maintained in high potassium and serum (K25+S). After 72 h, cultures were stained with calcine AM, which stains living cells. Phase-contrast images and the corresponding calcine AM photomicrographs are presented in Fig. 1. While virtually all of the Bax +/+ cells died by 72 h (compare Fig. 1, a and b with e and f), granule cells from Bax −/− mice did not undergo apoptosis (compare Fig. 1, c and d with g and h). To determine the number of surviving cells, we counted the number of neurons on photomicrographs of cultures stained with calcine AM after 0, 12, 24, 48, or 72 h in K5+S medium (Fig. 2). All the granule cells from Bax −/− mice were protected from cell death (Fig. 2, open triangles) while more than 90% of the wild-type granule cells died by 72 h (Fig. 2, open circles). Granule cells from heterozygous animals died completely by 72 h (Fig. 2, open squares), though the time course of death was slightly slower. Nuclei from Bax −/− cultures deprived of K+ for 72 h were indistinguishable from control cultures maintained in K25+S medium (data not shown), while Bax +/+ and Bax +/− cultures displayed characteristic apoptotic nuclear changes 6 h after switching to K5+S medium (data not shown).

In a more rigorous test of the ability of Bax −/− granule cells to resist apoptosis, we also determined the time course of death after both K+ and serum were removed (K5−S). Again, Bax −/− granule cells did not die while Bax +/+ and Bax +/− cells died completely by 72 h (Fig. 2); the death in Bax +/+ and Bax +/− was slightly faster when both serum and potassium were removed. Because removing K+ alone was an inherently simpler model in which only one source of trophic support was removed, this paradigm was used for all subsequent experiments.

We have previously shown that PI-3-K activity is increased by K+ depolarization (Miller et al., 1997). This in-
crease appears critical to the survival of depolarized neurons as shown by the ability of two inhibitors of PI-3-K to produce death indistinguishable from that caused by removal of high K+ (Miller et al., 1997). Because BCL-2 family members have been recently implicated in signaling pathways (Gajewski and Thompson, 1996; Wang et al., 1996; Zha et al., 1996), we directly tested the ability of Bax−/− cells to survive in the absence of PI-3-K activity. Neurons maintained for 7 d in vitro were switched to K25+ with 30 μM LY 294002, an inhibitor of PI-3-K. Viability was assessed after 48 h by calcein AM staining (Fig. 3). Similar to previous results (Miller et al., 1997), LY 294002 blocked the survival-promoting activity of K+ in Bax+/+ cells. Results from cultures of animals heterozygous for Bax were similar to those from wild type. In contrast, neurons from Bax−/− cultures survived in the presence of LY 294002, implying that Bax deficiency blocked apoptosis downstream of PI-3-K.

Bax−/− Neurons Are Not Protected From Excitotoxic Death

Overexpression of BCL-2 is neuroprotective in some models of stroke and excitotoxic injury (Linnik, 1996). Therefore, we tested whether the absence of BAX would be protective in an NMDA model of excitotoxic death in cerebellar granule cells. After 10 d in vitro, cultures from Bax+/+ and Bax−/− were stimulated with 10, 30, or 100 μM NMDA for 30 min and viability was assessed 24 h later by calcein AM staining (Fig. 4). In contrast to K+ deprivation or treatment with an inhibitor of PI-3-K, the absence of Bax was not neuroprotective in this excitotoxic paradigm. The lack of death in cultures simultaneously exposed to 100 μM NMDA and 150 nM MK-801, a highly potent noncompetitive NMDA receptor antagonist (Wong et al., 1986), demonstrated that the death was specific to stimulation of NMDA receptors.

BAX Is Not Required for the Early Decrease in Metabolic Parameters

The experiments described above indicate that BAX is required for mediating apoptosis in cerebellar granule cells. We were able to use this granule cell culture model to gain insight into where BAX functions in the cell death path-
way. One of the earliest changes in cerebellar granule cells undergoing PCD is a dramatic decrease in metabolic parameters such as glucose uptake and protein synthesis (Miller and Johnson, 1996; Nardi et al., 1997). We measured glucose uptake and protein synthesis in K^+-deprived, Bax^+/+ animals to determine at what point Bax^−/− cells are arrested in the cell death program and to provide an indication of the metabolic status of these cells. Cultures were switched to K5^+ for 2, 6, 12, 24, or 48 h, and metabolic parameters were measured. The dramatic early fall in glucose uptake was seen in cells from Bax^−/− animals; 2-deoxyglucose uptake fell to <20% of control within 2 h of K^+ deprivation (Fig. 5 A). The early fall in protein synthesis, as measured by uptake of l-[4,5-

\[\text{H}]\text{lucine, was also observed in Bax^−/− cultures (Fig. 5 B). However, Bax^−/− cells did maintain a low basal level of protein synthesis even after 48 h of K^+ deprivation. Therefore, BAX was not required for the early fall in metabolic parameters. Consistent with a decrease in metabolic parameters, granule cells from K^+-deprived Bax^−/− cultures, while alive, ceased to increase in diameter compared to those maintained in 25 mM potassium which continued to grow (Miller, T.M., personal observation). A similar relative decrease in soma diameter is seen in Bax^−/− sympathetic neurons deprived of NGF (Deckwerth et al., 1996).

BAX Is Not Required for Changes in mRNA Levels Associated with PCD

PCD of many cell types (Freeman et al., 1993), including cerebellar granule cells (D’Mello et al., 1993), is markedly attenuated by inhibitors of macromolecular synthesis, implying that transcription and translation of new gene products are important during cell death in these cells. Though most mRNA levels decline rapidly as cells die, we have previously identified increases in the mRNA levels of several genes during programmed cell death in granule cells and sympathetic neurons (Estus et al., 1994; Freeman et al., 1994; Miller and Johnson, 1996). The increase in the mRNA level of the AP-1 transcription factor c-Jun may be particularly important for cell death because microinjection of a dominant negative c-Jun construct (Ham et al., 1995) or neutralizing antibodies directed against c-Jun (Estus et al., 1994) significantly delays PCD of sympathetic neurons.

Whether the increase in c-jun mRNA and presumably the action of c-jun is downstream or upstream of BAX is unknown. To address this issue and examine other messages, cultures from Bax^+/+ and Bax^−/− animals were switched to K5^+ for 1, 3, 6, 9, 12, 18, 24, 48, or 72 h and mRNA was isolated, reverse transcribed, and selectively amplified by PCR. mRNA levels of cyclophilin declined rapidly in wild-type granule cells (Fig. 6, A and B); actin and neuron-specific enolase were similar to cyclophilin (data not shown). mRNA levels of these same messages in Bax^−/− cultures declined far less than in wild-type cultures reflecting the lack of death of Bax^−/− cells (Fig. 6, A and C). Similar to results seen in rat cerebellar granule cells (Miller and Johnson, 1996), mRNA levels for c-jun increased approximately fourfold in K^+-deprived wild-type granule cells (Fig. 6 B). c-jun mRNA also increased in K^+-deprived, Bax-deficient granule cells (Fig. 6 C), demonstrating that increases in c-jun were upstream of Bax.

c-fos mRNA levels increase in dying sympathetic neurons and the Fos family of proteins may be important for cell death in sympathetic neurons (Estus et al., 1994). Examination of c-fos mRNA levels in K^+-maintained granule cells was uninformative since K^+ depolarization itself drives the expression of c-fos (Ghosh et al., 1994). cyclin D1, a cell cycle regulator that increases in dying sympathetic neurons (Freeman et al., 1994), remained relatively constant in both wild-type and Bax-deficient animals (Fig. 6 A). Since this message level did not decrease in the wild-type cultures even after 120 h of K^+ deprivation (data not shown) when very few, if any, granule cells remained via-
ble, we concluded that the majority of the *cyclin D1* message level is in the few contaminating nonneuronal cells; therefore, we could not determine whether *cyclin D1* increased in the neurons. Glial fibrillary acidic protein (GFAP) is expressed in the astrocytes, which are the main contaminating nonneuronal cell. GFAP, as expected, remained relatively constant as the neurons died. *Bax* mRNA levels did not increase in wild-type granule cells undergoing apoptosis and, as expected, no *Bax* mRNA was expressed in *Bax*−/− cells (Fig. 6A).

mRNA levels of *caspase 3* (CPP32) increased in both wild-type and *Bax*-deficient cultures deprived of K⁺ (Fig. 6). Caspase 3 has been clearly implicated in several cell death paradigms (for review see Henkart, 1996) and in developmental neuronal cell death (Kuida et al., 1996), although whether increases in mRNA levels of caspases have any significance for cell death is unclear. The mRNA level of at least one other caspase, *caspase 2* (*Ich-1*), was not increased after K⁺ deprivation (data not shown).

**c-Jun Is Phosphorylated on Ser 63 in Both *Bax*+/+ and *Bax*−/− Cultures**

In addition to increases in mRNA levels, another indication of an increase in c-Jun activity is the phosphorylation of c-Jun on serines 63 and 73 of the transactivation domain (Binetruy et al., 1991; Smeal et al., 1991, 1992). Therefore, we determined the phosphorylation status of the c-Jun transactivation domain during PCD by immunostaining with an antibody that specifically recognizes the serine 63–phosphorylated form of c-Jun (Fig. 7). Cells maintained in K25+S medium (Fig. 7, a and e) had almost no staining. After 6 h of K⁺ deprivation, wild-type granule cells showed significant phosphorylation of c-Jun on serine 63 (Fig. 7 c). Similar to the parallel increases in *c-jun* mRNA levels in *Bax*+/+ and *Bax*−/− cultures, phospho-Jun staining also increased in *Bax*−/− granule cells deprived of K⁺ for 6 h (Fig. 7 g). Staining was not increased in the few nonneuronal cells in these cultures (data not shown). In nuclei counterstained with bisbenzimide (Fig. 7, b, d, f, and h), some K⁺-deprived, wild-type cells showed nuclear margination and chromatin condensation at 6 h (Fig. 7 d). The increase in c-Jun phosphorylation and *c-jun* mRNA in both wild-type and *Bax*−/− cultures indicates that BAX functions downstream of the increase in c-Jun activity that is associated with PCD.

**BAX Is Required for Increases in Caspase Activity**

Caspases have been implicated in several cell death models (for review see Henkart, 1996; Schwartz and Milligan, 1996). We examined whether caspases 2, 3, and 7 were activated after K⁺ deprivation. The activity of this subset of proteases can be measured by monitoring the cleavage of the fluorogenic substrate DEVD-AMC. In *Bax*+/+ and *Bax*−/− cells, DEVD-selective caspase activity increased to 18 times control levels by 8 h after K⁺ deprivation and then decreased as the cells died over the next 64 h. In stark contrast, granule cells from *Bax*−/− animals did not increase DEVD-specific caspase activity at any time after K⁺ deprivation (Fig. 8). These results indicate that BAX is
required for activation of this subset of caspases in response to removal of potassium.

Blocking Caspases Delays but Does Not Block Cell Death

Inhibiting caspases with peptide inhibitors blocks PCD in several models (Henkart, 1996; Schwartz and Milligan, 1996). For example, BAF or ZVAD-FMK, two inhibitors of caspases, have dramatic effects on saving sympathetic neurons from PCD induced by trophic factor deprivation (Deshmukh et al., 1996). We examined the effect of these compounds on K⁺ deprivation–induced cell death in granule cells. Neither compound was toxic to granule cells. After 3 d exposure to either 100 µM ZVAD or 100 µM BAF in K25⁺S medium, survival was 96 ± 1 and 103 ± 3%, respectively. In K5⁺S medium, while both BAF and ZVAD were able to delay PCD in granule cells at 12 h, neither afforded significant protection at later time points (Fig. 9 A). One possible explanation for the lack of protection was that BAF and ZVAD did not function as caspase inhibitors in these cells, perhaps because they did not effectively cross the plasma membrane. To rule out this possibility, we deprived cells of K⁺ in the presence of 100 µM BAF or 100 µM ZVAD and then measured caspase activity. Cells treated with either compound showed no increase in DEVD-AMC cleavage after K⁺ deprivation (Fig. 9 B), demonstrating that BAF and ZVAD did indeed penetrate granule cells and function as caspase inhibitors in these cells.

Further evidence that BAF was able to function inside cells was found in a TUNEL assay of K⁺-deprived granule cells. TUNEL serves as an in situ marker of DNA fragmentation (Gavrieli et al., 1992), one of the hallmarks of apoptosis. The number of TUNEL-positive cells increased markedly after switching cells from K25⁺S to K5⁺S (Fig. 10, d and e) from 14 to 84% (Fig. 10 g). Although BAF did not block cell death (Fig. 9 A), BAF blocked the increase in TUNEL positivity associated with depriving granule cells of potassium (Fig. 10, f and g).

A second method we used to inhibit caspase activity was expression of p35, a baculoviral protein. Recombinant p35 blocks the enzymatic activity of purified ICE, Ich-1, Ich-2, and CPP32 (caspases 1, 2, 4, and 3, respectively) (Bump et al., 1995; Xue and Horvitz, 1995). Expression of p35 delays PCD in NGF-deprived sympathetic neurons (Martinou et al., 1995) and a serum-deprived neuronal cell line (Rabizadeh et al., 1996).

Figure 7. c-Jun phosphorylation increases in both Bax +/+ and Bax −/− granule cells after K⁺ deprivation. Bax +/+ (a–d) and Bax −/− (e–h) cultures were switched to K25⁺S (a, b, e, and f) or K5⁺S (c, d, g, and h) medium for 6 h and immunostained with an antibody that specifically recognizes the ser-63 phosphorylated form of c-Jun (a, c, e, and g) and stained with the nuclear dye bisbenzimide (b, d, f, and h). Bar, 5 µm.

Figure 8. BAX is required for increases in caspase activity. Cultures were switched to K5⁺S medium, lysed after 4, 8, 12, 24, 48, or 72 h, and cleavage of DEVD-AMC was determined. Control cultures were switched to K25⁺S medium and treated identically. Data represent mean ± SD for triplicate measurements from one experiment and are representative of two additional independent experiments.
In this study, we demonstrated that PCD in cerebellar granule cells induced by K+ deprivation, K+/serum deprivation, or inhibition of PI-3-K requires BAX. In contrast, BAX was not required for excitotoxic cell death in granule cells since we found that Bax−/− granule cells were not protected from NMDA-induced cell death. Because Bax−/− granule cells did not die in response to K+ deprivation, we were able to use this model to define where BAX is acting in the pathway leading to apoptosis. We analyzed several metabolic and genetic events associated with PCD in granule cells and found that Bax deficiency did not affect these early events. On the other hand, we found that BAX was required for the activation of caspases since Bax+/+, but not Bax−/− cells cleaved a fluorogenic DEVD substrate in response to K+ deprivation. Our data suggest that while likely to be involved in cell death, caspases may not be solely responsible for causing cell death in granule cells since blocking these proteases with peptide inhibitors delayed, but did not significantly block, the loss of cells. These studies of Bax-knockout cells are consistent with BAX or BAK induction studies in which cell death also proceeded in the presence of caspase inhibitors (Xiang et al., 1996; McCarthy et al., 1997). From these results and previous studies, we are now able to define a sequence of events associated with PCD in granule cells (Fig. 12).

**Bax Deletion Does Not Appear to Result in Activation of Upstream Signal Transduction Pathways**

Survival-promoting agents, such as IGF-I and K+, are likely to block the initial activation of the cell death program by activating intracellular signaling pathways. We have previously shown that both K+ and IGF-I activate two intracellular signaling pathways, PI-3-K and mitogen-activated protein (MAP) kinase in these cells (Miller et al., 1997). MAP kinase is not likely to be regulating survival directly since inhibition of this pathway does not lead to cell death in granule cells (Miller et al., 1997) or sympathetic neurons (Creedon et al., 1996; Virdee and Tolkovsky, 1996). In contrast, inhibition of PI-3-K in granule cells in the presence of IGF-I or K+ induces cell death that is indistinguishable from potassium deprivation, including a similar time course of death, dependence on macromolecular synthesis, and characteristic morphology of apoptotic nuclei (Miller et al., 1997). Further support for the importance of the PI-3-K pathway in granule cells is the survival-promoting effect of overexpressing AKT (Dudek et al., 1997), a downstream target of PI-3-K (Bos, 1995; Franke et al., 1995). The ability of Bax−/− granule cells to survive without PI-3-K activity and the fact that metabolic changes and changes in mRNA levels still occur in Bax−/− cells implies that BAX lies downstream of both.

**BAX Is Not Required for Changes in Metabolic Parameters or mRNA Levels**

The early, dramatic fall in metabolic parameters that we saw in Bax−/− cultures is part of the cell death program in cerebellar granule cells (Miller and Johnson, 1996; Nardi et al., 1997), sympathetic neurons (Deckwerth and Johnson, 1993), and thymocytes (Makman et al., 1966; Munck, 1968; Cidlowski, 1982). Thus, we have hypothesized that these events may represent an early trigger for PCD. The early decreases in glucose uptake and protein

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**Figure 9.** Inhibitors of caspases do not block death, but do block DEVD-AMC cleavage. Cultures were switched to K5+S, K5+S plus 100 μM BAF, or K5+S plus 100 μM ZVAD-FMK. Control cultures were switched to K25+S medium. (A) After 12, 24, or 48 h neuronal survival was determined by calcein AM staining. (mean ± SD, N = 3 experiments) (B) After 8, 12, 18, 24, or 48 h cultures were lysed and assayed for DEVD-AMC cleavage. Fluorescence was measured after 20 min at room temperature (mean ± range, N = 2 experiments).
The synthesis rate were not affected by the Bax genotype. This suggests that the actions of BAX are not related to early signal transduction pathways mediating neuronal survival by trophic signals. This conclusion is further supported by the inability of PI-3-K inhibitors to induce cell death in Bax−/− cells. It is also consistent with previous observations that overexpression of BCL-2, while greatly retarding sympathetic neuronal death after NGF deprivation, has no effect on the decrease in protein synthesis that presages that death (Greenlund et al., 1995b).

The deletion of BAX also failed to block changes in mRNA levels, another step in the cell death program; c-jun mRNA increased in both Bax+/+ and Bax−/− cultures. Several reports have suggested that c-Jun may be important for cell death. Microinjection of neutralizing antibodies to c-Jun or a dominant negative c-jun construct delays the death of NGF-deprived sympathetic neurons (Estus et al., 1994; Ham et al., 1995). Dominant negative c-jun constructs also block cell death in human monocytic leukemia cells (U937) treated with ceramide (Verheij et al., 1996). An increase in c-Jun is evidently part of cell death in vivo. c-Jun increases in granule cells undergoing PCD in the weaver mouse (Gillardon et al., 1995) and in irradiated animals (Ferrer et al., 1996). c-Jun amino-terminal kinase (JNK) (Hibi et al., 1993) may be the kinase responsible for the increased phosphorylation on serine 63 of c-Jun in both Bax+/+ and Bax−/− cells (Fig. 7). Several reports have implicated this pathway during cell death (Xia et al., 1995; Chen et al., 1996; Latinis and Koretzky, 1996; Park et al., 1996; Verheij et al., 1996; Wilson et al., 1996). The increase in c-Jun both in vitro and in vivo, the fact that blocking c-Jun delays cell death, and increases in c-Jun phosphorylation during PCD imply that an increase in c-Jun is an important early occurrence during PCD. In PC12 cells, overexpression of Bcl-2 is able to block the increase in JNK activity associated with PCD, suggesting that the BCL-2 family functions upstream of c-Jun (Park et al., 1996). Our loss of function study with BAX is in apparent disagreement with these data. In cerebellar granule cells,
Caspase Activity

We examined the role of caspases in PCD in granule cells by determining changes in mRNA levels of caspase 3 (C22Q3) and increase in the activity of DEVD selective caspases. K^+ deprivation increased caspase 3 mRNA levels in Bax^+/− and Bax^−/− cultures. An increase in the message level of caspase 3 also occurs in response to focal ischemic injury (Asahi et al., 1997). Similarly, loss of expression of caspase 1 (ICE) in mammary epithelial cells correlates with the suppression of apoptosis by extracellular matrix (Boudreau et al., 1995). However, whether these changes in mRNA levels are important for cell death or lead to increases in activity of caspases is unclear.

We directly measured the activity of caspases 2, 3, and 7 and found that wild-type granule cells increased DEVD-specific substrate cleavage after K^+ deprivation (Fig. 8). Other groups have similarly reported that DEVD-AMC is cleaved in granule cells after K^+/serum deprivation (Armstrong et al., 1996; Nath et al., 1996). The increase in the activity of DEVD-selective caspases is an event that clearly occurs downstream of BAX in cerebellar granule cells (Fig. 8) since Bax^−/− cultures showed no increase in DEVD-AMC cleavage after K^+ deprivation. Similarly, overexpression of BCL-2 prevents activation of caspases in Jurkat cells (Armstrong et al., 1996; Chinnaiyan et al., 1996), in GT1-7 neural cells (Srinivasan et al., 1996), and in PC12 cells (Stefanis et al., 1996).

Caspase Inhibitors Do Not Block Granule Cell Death

We were surprised by the failure of the baculoviral protein p35 or pharmacological caspase inhibitors to block PCD in cerebellar granule cells. Although inhibiting caspases does delay cell death in granule cells up to 24 h (Nath et al., 1996; Schulz et al., 1996; Armstrong et al., 1997), our data indicate that these compounds did not offer any substantial long-term protection (Fig. 9). This contrasts with sympathetic neurons in which PCD is prevented completely for at least 7 by BAF (Deshmukh et al., 1996). These results suggest that granule cells have, in addition to a caspase-dependent pathway, a caspase-independent pathway downstream of BAX that insures cell death.

Our suggestion that at least two pathways exist downstream of BAX assumes that all potential caspases were effectively blocked in these studies. We demonstrated that DEVD-AMC cleavage was blocked completely in these cells, showing that the compounds used were able to penetrate the cells and function as caspase inhibitors. BAF, ZVAD-FMK (Armstrong et al., 1996; Cain et al., 1996; Deshmukh et al., 1996), and p35 (Bump et al., 1995; Xue and Horvitz, 1995) are nonspecific inhibitors with reasonable IC₅₀ₐₚₖₐₜₚₐₜₚₐₜ that block the activity of a wide spectrum of caspases. We cannot formally exclude the possibility that an atypical caspase might have been activated in granule cells in the presence of these inhibitors. Similarly, cell death in the presence of p35 might be accounted for by inadequate levels of protein expression.

The fact that cell death in the presence of caspase inhibitors was TUNEL-negative, while K^+ deprivation induced was TUNEL-positive, provided further evidence for the ability of caspase inhibitors to function inside of cells. The nuclear morphology of dying BAX- and ZVAD-treated granule cells may also be an indication that these compounds blocked caspases. While BAX- and ZVAD-treated nuclei did condense, we found no evidence for margination or clumping of the chromatin typically observed in apoptotic cells, though these changes were apparent in untreated, K^+-deprived cells (Miller, T.M., personal observation). The ability of caspase inhibitors to block lamin proteolysis (Lazebnik et al., 1995) may account for the lack of margination and chromatin clumping (Rao et al., 1996). In addition to demonstrating that these caspase inhibitors did function within cells, these data raise the possibility that the modestly slower, caspase-independent cell death in granule cells differs fundamentally from the cell death that normally occurs after K^+ deprivation when caspases are unimpeded. Further studies of this caspase-independent, TUNEL-negative cell death may elucidate important differences between these two cell death pathways.

Evidence in a different system using an alternative approach has also recently suggested a BAX-dependent, protease-independent mechanism of cell death. BAX overexpression in Jurkat cells leads to an apoptotic-like death that is not blocked by caspase inhibitors, calpain inhibitors, serine protease inhibitors, granzyme B inhibitors, or proteasome inhibitors (Xiang et al., 1996). In these overexpressing Jurkat cells, as observed here, caspase inhibitors do block DNA fragmentation and cleavage of substrates for caspases; however, these cells still die. In Jurkat cells, a fall in mitochondrial membrane potential and an increase in ROS occurs (Xiang et al., 1996). These mitochondrial changes and the membrane localization of BAX suggest that a mitochondria-dependent cell death predominates in BAX gain of function experiments (Xiang et al., 1996). Data here in the experimental setting of BAX loss-of-function provide support for the possibility that a non–caspase-dependent, TUNEL-negative, cell death pathway resides downstream of BAX.

In summary (Fig. 12), K^+ and IGF-I block the activation of the cell death program in granule cells. When these agents are removed and the program is activated, MAP kinase activity, PI-3-K activity, metabolic parameters, and most mRNA levels decrease, while some mRNA levels, e.g., c-Jun, increase. Our data from the Bax^−/− mice place BAX downstream of these changes. The PCD events subsequent to BAX include increased caspase activity and some other change(s) that promote DNA fragmentation, chromatin condensation, and cell death.
Bax −/− granule cell cultures offer an informative perspective on cell death because these cells clearly progress through part of the apoptotic program and then are completely halted. These cultures should be a valuable tool for further ordering the molecular pathways leading to cell death, for defining the role of the BCL-2 family in apoptosis, and, potentially, for identifying a caspase-independent cell-death pathway. Finally, Bax −/− animals bred to mice harboring various cerebellar mutations will determine whether BAX deletion can also rescue “diseased” granule cells in vivo. Assessing both the extent of neuroprotection and the recovery of cerebellar function may offer important insights into how modulation of the BCL-2 family may affect neurological disease.

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