Requirement for cGMP in Nerve Cell Death Caused by Glutathione Depletion

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Abstract. Glutathione depletion occurs in several forms of apoptosis and is associated with Parkinson’s disease and HIV toxicity. The neurotransmitter glutamate kills immature cortical neurons and a hippocampal nerve cell line via an oxidative pathway associated with glutathione depletion. It is shown here that soluble guanylyl cyclase (sGC) activity is required for nerve cell death caused by glutathione depletion. Inhibitors of sGC block glutamate toxicity and a cGMP analogue potentiates cell death. Glutamate also induces an elevation of cGMP that occurs late in the cell death pathway. The resultant cGMP modulates the increase in intracellular calcium that precedes cell death because sGC inhibitors prevent calcium elevation and the cGMP analogue potentiates the increase in intracellular calcium. These results suggest that the final pathway of glutamate-induced nerve cell death is through a cGMP-modulated calcium channel.

Glutathione is a cysteine-containing tripeptide (γ-glutamylcysteinylglycine) that exists in both the reduced (GSH)1 and the oxidized states (GSSG). GSH is the predominant form within the cell, usually accounting for greater than 99% of the total glutathione (Meister and Anderson, 1983). GSH plays an important role in protecting cells from oxidative damage and regulates several aspects of cellular metabolism. The synthesis of GSH is regulated by the enzyme γ-glutamyl-cysteine synthetase and its precursor molecule, cysteine, which is present at low concentration within the cell. Low levels of intracellular GSH are linked to a variety of pathological conditions, such as HIV (Herzenberg et al., 1997) and Parkinson’s disease (Perry et al., 1982; Sofic et al., 1992; Sian et al., 1994). This association appears to be significant because HIV-infected lymphocytes that contain decreased intracellular GSH are more likely to undergo apoptosis (Staal et al., 1992; Ameisen et al., 1995). Artificially elevating GSH by N-acetylcysteine prolongs the survival of the HIV-infected cells (Herzenberg et al., 1997). In the nervous system, there is an early and highly specific decrease in GSH in the substantia nigra of Parkinson’s disease patients (Perry et al., 1982; Sofic et al., 1992; Sian et al., 1994), and the artificial depletion of GSH both induces dopaminergic neuronal cell death in vitro (Jenner and Olanow, 1996) and potentiates the toxicity of 6-hydroxydopamine and 1-methyl-4-phenylpyridinium (MPP+) in vivo (Pileblad et al., 1989; Wullner et al., 1996). Together, these data suggest that GSH depletion directly contributes to cell death in a variety of cell types.

GSH depletion is observed in models of apoptotic cell death, including glucocorticoid-induced thymocyte apoptosis (Beaver and Waring, 1995; Slater et al., 1995) and Fas/APO-1–induced T lymphocyte apoptosis (van den Dobbelsteen et al., 1996). Several mechanisms account for the depletion of GSH. (a) The production of reactive oxygen species and the increased requirement for glutathione peroxidase may lead to the consumption of GSH. (b) The activation of a transmembrane export channel appears to be responsible for the decline in intracellular GSH during apoptosis in lymphocytes (van den Dobbelsteen et al., 1996) and U937 human monocytic cells (Ghelli et al., 1995). (c) When persistently exposed to the neurotransmitter glutamate, immature cortical neurons, which do not have ionotropic glutamate receptors, are depleted of intracellular GSH through the competition by glutamate for cystine uptake (Murphy and Baraban, 1990; Murphy et al., 1990). Elevated levels of extracellular glutamate interfere with the exchange of glutamate with cystine through a cystine/glutamate antiporter, which normally carries cystine into the cell. This leads to a decrease in the level of intracellular...
lar cystine and its reduction product cysteine, thereby causing a decrease in the level of GSH. This mechanism, called oxidative glutamate toxicity, has also been described in a hippocampal nerve cell line HT22 (Davis and Maher, 1994), in a nerve-glia hybrid cell line N18-RE-105 (Murphy et al., 1989), and in primary oligodendrocytes (Oka et al., 1993). When artificially depleted of GSH, immature cortical neurons also undergo programmed cell death (Ratan et al., 1994).

The steps linking GSH depletion to neuronal cell death are largely unknown. We have been studying this pathway using glutamate treatment of immature cortical neurons and a neuronal cell line. Recently, we found that depletion of GSH activates neuronal 12-lipoxygenase (12-LOX), which leads to the production of reactive oxygen species, the increase in intracellular Ca\(^{2+}\), and ultimately to cell death (Li et al., 1997). The experiments outlined below extend these studies to show that the soluble guanylyl cyclase (sGC) cGMP pathway is involved in nerve cell death caused by GSH depletion. This investigation was predicated upon the following observations. First, Ca\(^{2+}\) elevation is required for oxidative glutamate-induced neuronal cell death since the removal of extracellular Ca\(^{2+}\) prevents cell death (Murphy et al., 1989; Davis and Maher, 1994) and the intracellular Ca\(^{2+}\) level increases during cell death (Li et al., 1997). One possible regulator of Ca\(^{2+}\) elevation is cGMP since cGMP can directly or indirectly modulate some ion channels (Yau, 1994; Kaupp, 1995; Finn et al., 1996). Second, LOX activation is required for glutamate toxicity (Li et al., 1997), and LOX metabolites activate sGC (Snider et al., 1984; Brune and Ulrich, 1991). This paper reports the first evidence for a role of sGC in mediating programmed cell death caused by glutathione depletion.

**Materials and Methods**

**Cell Cultures**

Mouse hippocampal HT22 cells (Davis and Maher, 1994) are derived from the HT4 cell line (Morimoto and Koshland, 1989) and are propagated in DME (Vogt and Dulbecco, 1963) supplemented with 10% FBS. Primary cortical neurons were prepared from embryonic day 17 Sprague-Dawley rats as described (Abe et al., 1990). After dissociation from brain tissues with trypsin and DNase I, cells were maintained in MEM supplemented with 30 mM glucose, 2 mM glutamine, 1 mM pyruvate, and 10% FBS.

**Cell Viability Assay**

Cell viability was determined by one of three cell counting or MTT assays in 96-well plates. The MTT assays measure the ability of cells to metabolize 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT) and is often used to measure cellular proliferation (Mosmann, 1983). In this system, it correlates with cell viability as determined by trypan blue exclusion and a colony-forming assay (Davis and Maher, 1994). The assay medium contained 5% dialyzed FBS for the glutamate toxicity assay or horse serum for the assay of buthionine sulfoximine (BSO) toxicity (Li et al., 1997). Fresh preparations of BSO were used. For the MTT assay, cells were dissociated and seeded into 96-well microtiter plates at a density of 2.5 × 10\(^4\) or 5 × 10\(^4\) cells per well in 100 μl medium for HT22 cells and cortical neurons, respectively. The next day cells were treated with various reagents according to the experimental design. 20 h after the treatment, 10 μl of MTT solution (5 mg/ml) was added to each well and incubated for 3 h. 100 μl of solubilization solution (50% dimethylformamide, 20% SDS, pH 4.8) was then added to the wells, and the next day the absorbance level increases during cell death (Li et al., 1997). One possible regulator of Ca\(^{2+}\) elevation is cGMP since cGMP can directly or indirectly modulate some ion channels (Yau, 1994; Kaupp, 1995; Finn et al., 1996). Second, LOX activation is required for glutamate toxicity (Li et al., 1997), and LOX metabolites activate sGC (Snider et al., 1984; Brune and Ulrich, 1991). This paper reports the first evidence for a role of sGC in mediating programmed cell death caused by glutathione depletion.

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**Glutathione, GMP, and Ca\(^{2+}\) Measurements**

For the glutathione, GMP, and Ca\(^{2+}\) measurements to be described below, HT22 cells were seeded at 5 × 10\(^4\) cells/100 mm and the next day were treated according to the experimental design. Cells were then collected at indicated times for the above assays. Glutathione was determined by the recycling assay based on the reduction of 5,5-dithiobis(2-nitrobenzoic acid) with glutathione reductase and NADPH (Tietz, 1989). Sample preparation and assay procedures were described elsewhere (Li et al., 1997).

For cGMP determination, HT22 cells were treated with glutamate for various times, collected, and resuspended in 0.1 N HCl. After 1 h on ice, the samples were centrifuged in a microfuge. The supernatant was neutralized and assayed for cGMP content using an EIA cGMP assay kit from Amersham International (Buckinghamshire, England). The pellet was dissolved in 0.1 N NaOH, and protein content was determined using a commercial kit from Pierce Chemical Co. (Rockford, IL). cGMP content was calculated per milligram protein and presented relative to the controls.

The intracellular ionized calcium concentration was determined by flow cytometry using ratiometric analysis. HT22 cells were loaded with 1 μM Indo-1 at 37°C for 30 min in the presence of 0.005% Pluronic F-127 in DME containing 10% FCS. After incubation, cells were collected, washed, and resuspended in phenol red-free Hepes-buffered DME supplemented with 2% dialyzed FBS. Cells were allowed a 15-min recovery period to hydrolyze the ester bond before being analyzed with a FACStar plus flow cytometer (Becton Dickinson, Mountain View, CA). The fluorescence light from the two emission peaks of Indo-1, 410 nm (violet) and 485 nm (green), was collected, and the ratio of violet to green, which is proportional to Ca\(^{2+}\) concentrations (Grynkiewicz et al., 1985), was obtained. 10,000 viable cells were analyzed in each assay.

**Reagents**

Tissue culture reagents were obtained from Gibco BRL (Gaithersburg, MD). The fluorescent dye Indo-1 acetoxymethylester was obtained from Molecular Probes (Eugene, OR). LY83583, N\(^6\)-methyl-t-arginine, nifedipine, N\(^{2}\)-nitro-t-arginine, and nitrosoarginine are required for oxidative glutamate toxicity (Li et al., 1997). One target for LOX metabolites is sGC (Snider et al., 1984; Brune and Ulrich, 1991). To determine if sGC is involved in glutamate toxicity, we first tested the effect of various inhibitors of sGC on the survival of HT22 cells after exposure to glutamate. HT22 cells were incubated with 5 mM glutamate in the presence of several concentrations of the inhibitors for 20 h. Cell viability was then determined by MTT reduction, a viability assay that correlates in this system with trypan blue exclusion and colony formation assays (Davis and Maher, 1994). Under these conditions, glutamate alone caused the complete lysis of cells as assayed by both MTT reduction (Fig. 1 A) and microscopic examination. Treatment of the...
Inhibitors of sGC Also Prevent Neuronal Cell Death Induced by Buthionine Sulfoximine

Since the activation of 12-LOX has been experimentally linked to the reduced level of intracellular GSH (Li et al., 1997), it was asked if GSH depletion is also sufficient to activate sGC-mediated cell death. To determine if sGC is also involved in neuronal cell death associated with GSH depletion, the effect of sGC inhibitors on BSO toxicity was examined. BSO, a specific inhibitor of \( \gamma \)-glutamylcysteine synthetase, the rate-limiting enzyme in GSH synthesis, depletes intracellular GSH and causes cell death in a time- and dose-dependent manner in both HT22 cells and primary cortical neurons (Li et al., 1997). An overnight exposure of HT22 cells or primary cortical neurons to 50 \( \mu \)M BSO causes glutathione depletion (Fig. 2) and a dramatic loss of cell viability (Fig. 1, C and D). sGC inhibitors LY83583, methylene blue, and \( N \)-methyl-hydroxylamine all block BSO toxicity in a manner similar to that of glutamate, suggesting that sGC is directly linked to neuronal cell death caused by GSH depletion. There are, however, differences in the pharmacology of sGC inhibitors that prevent glutamate- and BSO-induced cell death. These differences may be due to the fact that at least the early events are different for these two models of cell death, because glutamate interferes with the cystine uptake while BSO directly inhibits GSH synthesis.

**sGC Inhibitors Do Not Affect the Ability of Glutamate or BSO to Deplete GSH**

To determine whether sGC inhibitors block the toxicity of glutamate and BSO by affecting their ability to deplete GSH, we compared intracellular glutathione levels in HT22 cells treated with these agents as a function of time. Fig. 2 shows that sGC inhibitor LY83583 did not block the depletion of GSH by either glutamate or BSO. None of the other sGC inhibitors blocked glutathione depletion either (data not shown). In the case of BSO treatment, the addition of LY83583 accelerated the depletion of GSH (Fig. 2).
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Figure 2. sGC inhibitor LY83583 does not prevent the depletion of glutathione by glutamate or BSO. HT22 cells were treated with either 5 mM glutamate or 50 μM BSO in the presence or absence of 2 μM LY83583 for various times. The cells were collected and assayed for glutathione levels and protein content. The data are presented relative to controls (0 h, no treatment). The level of glutathione was 12.4 ± 0.62 nmol/mg protein and 8.08 ± 0.08 nmol/mg protein for cells grown in FCS-containing medium and horse serum–containing medium, respectively. Horse serum was used when BSO toxicity was studied because it gave more sensitive and consistent results (Li et al., 1997).

2). This is probably due to the fact that LY83583 is also capable of inhibiting glutathione reductase (Luond et al., 1993) and therefore the regeneration of GSH from GSSG. These data, showing that sGC inhibitors prevent cell death but not GSH depletion, support the previous argument that GSH depletion caused by glutamate is not in itself sufficient to cause cell lysis (Murphy et al., 1989).

The Activation of sGC Occurs Near the Time of Cell Death

Since sGC inhibitors block toxicity, it is likely that the enzyme is activated to produce cGMP. To determine if there is an increase in the level of cGMP, intracellular cGMP levels of HT22 cells treated with 5 mM glutamate for various times were assayed. Fig. 3 A shows that the level of cGMP starts to increase 8 h after glutamate treatment. Under the conditions used, cells also begin to die at ~8 h after the addition of glutamate. The increase in cGMP was prevented by treatment of cells with 1 μM LY83583 (data not shown). Therefore, sGC activation occurs near the time of cell death.

To independently determine when in the cytotoxicity pathway sGC is activated, HT22 cells were treated with glutamate, and at various times afterwards LY83583 was added, followed by a cell viability assay at 20 h. Alternatively, glutamate was added and then removed at various times after its initial addition to the cultures. LY83583 was able to inhibit glutamate toxicity even when applied up to 8 h into the cell death process (Fig. 3 B). The protection conferred by LY83583 started declining at 8 h after addition of glutamate, which is the same time that glutamate was no longer required for cell death (Fig. 3 B). After ~8 h of exposure to glutamate, HT22 cells gradually initiate cell lysis, which is complete after ~15 h. However, surviving cells can still be rescued by LY83583 even during the late period of cell death. For example, if 1 μM LY83583 is added to cultures when 73% of cells are dead, the remaining 27% of the cells survive when examined 24 h later. These observations suggest that the activation of sGC occurs at a point that is very close to cell lysis.

A Cell-permeable cGMP Analogue Potentiates Glutamate Toxicity

If cGMP is involved in the cell death pathway, then exoge-
that the inhibition of sGC will affect the activity of these targets. If they are in the cell death pathway, then their inhibition will also block cell death. We examined whether PKG is involved in cell death using KT5823, a highly selective inhibitor of PKG with an IC$_{50}$ of 0.23 μM (Ito and Karachot, 1990). Fig. 4 D shows that KT5823 was unable to block cell death even at concentration up to 100 μM, suggesting that PKG is not involved in the cell death caused by GSH depletion.

**sGC/cGMP Regulates the Elevation of Ca$^{2+}$**

Another potential target for cGMP is the activation of Ca$^{2+}$ channels, which play an important role in oxidative glutamate toxicity. The removal of extracellular Ca$^{2+}$ or the addition of the Ca$^{2+}$ channel blocker CoCl$_2$ inhibits glutamate toxicity (Murphy et al., 1989; Davis and Maher, 1994), and glutamate induces the elevation of intracellular Ca$^{2+}$ (Li et al., 1997). These data suggest that the increased intracellular Ca$^{2+}$ is derived from extracellular medium rather than intracellular calcium pools. Initial experiments were done to identify the specific channels involved in cell death. The influx of Ca$^{2+}$ may be via voltage-dependent channels, cGMP-regulated channels, Na$^+$/Ca$^{2+}$ exchangers, or nonspecific membrane leakage. Membrane leakage is unlikely since CoCl$_2$ prevents cell death (Murphy et al., 1989; Davis and Maher, 1994). Replacement of Na$^+$ by Li$^+$ did not prevent cell death (data not shown), which excludes the involvement of a Na$^+$/Ca$^{2+}$ exchanger. Various inhibitors of Ca$^{2+}$ channels were then tested for their ability to prevent cell death induced by glutamate. These included the L-type channel inhibitors nifedipine, dilitizam, verapamil, and nimodipine, and the N-type channel inhibitor ω-conotoxin GVIA. None of these was protective at concentrations up to toxic doses (data not shown). Therefore, it is unlikely that L- or N-type channels or Na$^+$/Ca$^{2+}$ exchangers are involved in the cell death. The involvement of a cGMP-regulated Ca$^{2+}$ channel cannot be tested biochemically because no specific inhibitors exist (Finn et al., 1996). Although pimozide and D600 can block these channels in some cases (Finn et al., 1996), they were not effective in preventing cell death caused by glutathione depletion (data not shown). If, however, it were possible to demonstrate that cGMP-gated Ca$^{2+}$ channels are opened. Fig. 5 A shows that CPT-cGMP indeed potentiates Ca$^{2+}$ elevation. CPT-cGMP greatly enhances the level of intracellular Ca$^{2+}$ in cells exposed to marginally toxic (2 mM) concentrations of glutamate.

It was then asked if there is a temporal relationship between sGC activation and Ca$^{2+}$ elevation. Cells were exposed to LY83583 and CoCl$_2$ at various times after the addition of glutamate, and cell viability was assayed 20 h after the initial addition of glutamate. Fig. 3 B shows that LY83583 and CoCl$_2$ function in parallel in terms of maximal protection. Both agents maintain maximal protection up to 8 h past the addition of glutamate, after which cell lysis occurs gradually over the next few hours. Therefore, both sGC activation and Ca$^{2+}$ elevation occur near the time of cell death.

If sGC activation is required for Ca$^{2+}$ elevation, then its inhibition should block the glutamate-induced accumulation of intracellular Ca$^{2+}$. We therefore investigated the effect of sGC inhibitors on the intracellular Ca$^{2+}$ profile during the glutamate treatment. The intracellular Ca$^{2+}$ response to glutamate was first determined by flow cytometry using ratiometric analysis. Intracellular Ca$^{2+}$ content is proportional to the ratio of fluorescence intensities from the two emission peaks of the Ca$^{2+}$-bound and unbound Indo-1 dye (Gryniewicz et al., 1985) and was arbitrarily defined as low (the ratio is less than 50), medium (the ratio is between 50 and 100), and high (the ratio is between 100 and 250). In control cells, only about 2% of the cells had high levels of Ca$^{2+}$, with very few cells containing the high Ca$^{2+}$ level (Fig. 5 B; percentiles of cells in each class were derived from the scatter plots shown). Treatment with 5 mM glutamate for 12 h resulted in a dra-
matic increase in the percentages of cells containing medium to high levels of Ca\(^{2+}\) (Fig. 5B). 12 h after the exposure of cells to glutamate, \(\sim 20\%\) of the cells were alive. Of these, only 10–20\% had medium to high levels of Ca\(^{2+}\) (Fig. 5B and data not shown). The fact that the high Ca\(^{2+}\)-containing cells accounted for such a minority of cells at the time when cells were dying rapidly again suggests that Ca\(^{2+}\) elevation occurs very close to cell lysis. The rise of Ca\(^{2+}\) level during the incubation of cells with glutamate was prevented by sGC inhibitors, while these inhibitors had no effect on control cells (Fig. 5B and data not shown). Therefore, sGC inhibitors block glutamate-induced Ca\(^{2+}\) elevation in HT22 hippocampal cells. It was not, however, possible to do these experiments in primary cultures because of unstable baselines due to spontaneous cell death in the short term cultures.

**sGC-mediated Glutamate Toxicity Is through a Mechanism Independent of NO and Carbon Monoxide**

Since several of the inhibitors used above do not inhibit the basal activity of sGC (see Discussion), the activation of sGC is probably not due to its transcriptional upregulation, but rather due to the induction of sGC activators. NO and carbon monoxide are activators of sGC. If they are responsible for the sGC activation observed in the cell death, these activators should also be a target for blocking glutamate toxicity. Therefore, we determined if the inhibition of their synthesis is able to block glutamate toxicity.

Various inhibitors of NO synthase (NOS) were tested at several concentrations. \(\text{NG}^\text{G}\)-monomethyl-l-arginine methyl ester, a specific inhibitor of NOS, did not attenuate glutamate or BSO toxicity in HT22 cells or in primary cortical neurons (Fig. 1). Other NOS inhibitors, including 7-nitroindazole (a specific inhibitor for neuronal NOS-1) (up to 0.25 mM), \(\text{NG}^\text{G}\)-methyl-l-arginine (up to 1.0 mM), and \(\text{NG}^\text{G}\)-nitro-l-arginine (up to 1.0 mM), also did not show any protective effect on glutamate toxicity (data not shown). Similarly, tin protoporphyrin, an inhibitor of heme oxygenase and carbon monoxide production, only had minimal effects on glutamate toxicity at near toxic concentrations (data not shown).

**Discussion**

The data presented above indicate a requirement for sGC/cGMP in nerve cell death caused by GSH depletion. First, three structurally unrelated inhibitors of sGC all block glutamate or BSO toxicity (Fig. 1) at concentrations that inhibit sGC activity or cause cGMP reduction in vitro. Second, glutamate induces an increased production of cGMP (Fig. 3). Third, a membrane-permeable cGMP analogue, CPT-cGMP, potentiates glutamate toxicity (Fig. 4). Lastly, sGC inhibitors block the glutamate-induced increase in intracellular Ca\(^{2+}\) required for toxicity (Fig. 5). Therefore, the generation of cGMP and the subsequent activation of a Ca\(^{2+}\) channel are events occurring in GSH depletion–induced nerve cell death.

Of the sGC inhibitors used here, hydroxylamine and its analogue, \(\text{N}\)-methyl-hydroxylamine, competitively bind to the heme group associated with sGC, inhibiting sGC acti-
vation (Deguchi et al., 1978). However, the other sGC inhibitor, LY83583, appears to be relatively specific for sGC in various studies (Schmidt et al., 1985; Mulsch et al., 1988). The mechanism by which LY83583 inhibits sGC is not completely known, but the inhibitory effect appears to require the intracellular reduction of the compound (Mulsch et al., 1988). However, LY83583 inhibits glutathione reductase, thereby causing an increase in the level of GSSG (Luond et al., 1993). This effect may contribute to the ability of LY83583 to inhibit sGC since high levels of GSSG can cause an irreversible loss of sGC activity (Graff et al., 1978; Frey et al., 1980; Wu et al., 1992; Mayer et al., 1995).

Both cytotoxic and cytotropic roles for cGMP have been described in the nervous system. For example, cGMP prevents motor neuron degeneration (Weil and Greene, 1984) and protects against excitatory amino acid–induced damage in cerebellar slices (Garthwaite and Garthwaite, 1988). cGMP may also be involved in the excitotoxic activities of the secreted forms of β-amyloid precursor in hippocampal neurons (Barger et al., 1995) and mediate the survival effect of NO on trophic factor-deprived PC12 cells and sympathetic neurons (Farinelli et al., 1996).

In the contrast, the accumulation of cGMP is associated with retinal degeneration (Lolley et al., 1977; Bowes et al., 1990) and possibly mediates excitatory amino acid–induced cytotoxicity in cortical neurons (Frandsen et al., 1992; Lustig et al., 1992). The experiments presented above demonstrate that sGC/cGMP is also a component in the cell death pathway in nerve cells depleted of GSH.

It is likely that cGMP is responsible for the increase in intracellular Ca2+ required for glutamate toxicity. The elevation of cGMP occurs late in the death pathway (Fig. 3), and the increase in intracellular Ca2+ also occurs late. HT22 cells start to die ~8 h after the addition of glutamate, while sGC inhibitors are able to rescue cells even when the majority of cells are dead, suggesting that sGC activation occurs very shortly before actual cell death. The elevation of Ca2+, which was blocked by sGC inhibitors, occurs only in 10–20% of cells at any time during the period of disintegration (Fig. 5 B), suggesting that Ca2+ accumulation immediately precedes cell death in individual cells. Additional evidence supporting the relevance of Ca2+ elevation with sGC/cGMP comes from the observations that: (a) CPT-cGMP potentiates the elevation of Ca2+ induced by glutamate (Fig. 5 A); (b) other potential regulators of cGMP such as PKG (Fig. 4) and cGMP-regulated phosphodiesterases are not involved in cell death; and (c) inhibitors of the other classes of identified Ca2+ channels are unable to prevent cell death. Therefore, HT22 cells probably possess an unidentified cGMP-modulated Ca2+ channel (Finn et al., 1996).

Ca2+ is known to be involved in programmed cell death (McConkey and Orrenius, 1994). However, the regulator and the effector molecule for these Ca2+ fluxes are largely unknown. Recently, it has been shown that Ca2+ influx in glucocorticoid-induced lymphocyte apoptosis is mediated through the inositol 1,4,5-triphosphate receptor pathway (Khan et al., 1996). It is therefore likely that various regulators of Ca2+ exist to control cell death in different environments.

In summary, it is shown in a clonal cell line and primary cortical neurons that the elevation of cGMP, which likely results from sGC activation, is a critical step in the nerve cell death caused by GSH depletion. The activation of sGC is via an NO-independent mechanism. cGMP then induces Ca2+ influx, which immediately precedes cell death. If the observation can be extended to in vivo situations, then intervention of the sGC/cGMP pathway could be beneficial to individuals suffering from PD or other pathologies associated with GSH depletion.

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References


Herzenberg, L.A., S.C. De Rosa, J.G. Dubs, M. Roederer, M.T. Anderson,