Blockade of Gap Junctions In Vivo Provides Neuroprotection After Perinatal Global Ischemia

Mara H. de Pina-Benabou; Vanessa Szostak; Andreas Kyrozis; David Rempe; Daniela Uziel; Marcia Urban-Maldonado; Salomon Benabou; David C. Spray; Howard J. Federoff; Patric K. Stanton; Renato Rozental

Background and Purpose—We investigated the contribution of gap junctions to brain damage and delayed neuronal death produced by oxygen-glucose deprivation (OGD).

Methods—Histopathology, molecular biology, and electrophysiological and fluorescence cell death assays in slice cultures after OGD and in developing rats after intrauterine hypoxia-ischemia (HI).

Results—OGD persistently increased gap junction coupling and strongly activated the apoptosis marker caspase-3 in slice cultures. The gap junction blocker carbenoxolone applied to hippocampal slice cultures before, during, or 60 minutes after OGD markedly reduced delayed neuronal death. Administration of carbenoxolone to ischemic pups immediately after intrauterine HI prevented caspase-3 activation and dramatically reduced long-term neuronal damage.

Conclusions—Gap junction blockade may be a useful therapeutic tool to minimize brain damage produced by perinatal and early postnatal HI. **(*Stroke*. 2005;36:2232-2237.)**

Key Words: apoptosis ■ carbenoxolene ■ connexin ■ gap junction ■ ischemia

Gap junction channels allow exchange of intracellular ions and molecules as large as 1 kDa between dying and viable brain cells, exchanged that has been suggested to be detrimental or beneficial, depending on the nature of the insult (ie, ischemia or trauma).[1] Apoptotic and necrotic signals may spread from stressed to neighboring cells through gap junctions, amplifying the extent of injury.[2–5] Agents that close gap junctions, such as insulin,[6] insulin-like growth factor-1,[7] growth hormone,[8] and octanol,[9] have been reported to be neuroprotective, but intercellular communication via gap junctions has also been suggested to confer resistance to cellular injury after ischemia,[10,11] making the role of gap junctions in response to ischemia unclear.

Materials and Methods

Carbenoxolone Application

In vitro, 75 μmol/L carbenoxolone (CBX; disodium salt; Sigma) was added to slice culture medium.[12] In vivo, CBX was administered intraperitoneally twice after intrauterine hypoxia-ischemia (HI), a loading dose (75 mg/kg; ≈150 μmol/L) immediately after recovery of respiration, and a second (30 mg/kg) 12 hours later. Similar in vivo dosing regimens desynchronize spinal motor neuron firing[13] and directly block dye coupling of anterior subventricular cells[14] and retinal neurons.[15]

Organotypic Hippocampal Slice Cultures

All animal procedures were in accordance with the National Institutes of Health *Guide for Care and Use of Laboratory Animals* approved by institutional animal ethics committees of Albert Einstein College Medicine and New York Medical College.

Organotypic hippocampal slice cultures[16] were prepared from 9- to 12-day-old Sprague-Dawley rats (Taconic) of both sexes and cultured on semipermeable inserts (Millicell CM) over 1 mL medium (50% mimimum essential medium; 25% Hanks' balanced salt solution, 25% heat-inactivated horse serum, 13 mmol/L HEPES, and 2.5 mg/mL glucose). After 6 to 10 days, slice cultures were exposed to oxygen-glucose deprivation (OGD) by transfer to glucose-free medium (in mmol/L: 1.25 $CaCl_2$, 0.9 $MgSO_4$, 5.4 KCl, 0.44 KH_2PO_4, 137 NaCl, 4.2 $NaHCO_3$, 0.35 NaH_2PO_4, 16.7 HEPES, and 27.5 mannitol) in a box gassed with 95% N_2/5% CO_2 for 45 minutes, then returned to normal medium and CO_2 until measuring neuronal death.

Propidium Iodide Fluorescence

Media containing 1 μmol/L propidium iodide (PI) was applied for 10 minutes to slices, washed, and PI-labeled dead cells imaged using fluorescein isothiocyanate filters. Fluorescence intensity was measured in equal areas within CA1 stratum pyramidale.

Nucleosomal DNA and Semiquantitative Polymerase Chain Reaction

Nucleosomal DNA fragments were detected using the Cell Death ElisaPlus Kit (Boehringer-Mannheim). RT-PCR assays were per-

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From the Departments of Cell Biology and Anatomy (M.H.dP.-B., P.K.S., R.R.), Neurology (P.K.S.), Obstetrics (R.R.), Pediatrics, and Anesthesiology (R.R.), New York Medical College, Valhalla; Department of Physiology (M.H.dP.-B.), University of São Paulo, Brazil; Department of Neurology (V.S., A.K.) and Neurosciences (M.U.-M., D.C.S.), Albert Einstein College of Medicine, Bronx, NY; Department of Neurology (A.K.), Eginition Hospital, University of Athens, Greece; Department of Anatomy (D.U.), Federal University of Rio de Janeiro, Brazil; Division of Neurosurgery (S.B.), Beneficencia Portuguesa Hospital, Sao Paulo, Brazil; Aab Institute for Biomedical Sciences (D.R., H.J.F.), University of Rochester School of Medicine and Dentistry, New York.

Correspondence to Renato Rozental, MD, PhD, Department of Cell Biology and Anatomy, BSB Room A21, New York Medical College, 95 Grasslands, Valhalla, NY 10595. E-mail r_rozental@nymc.edu

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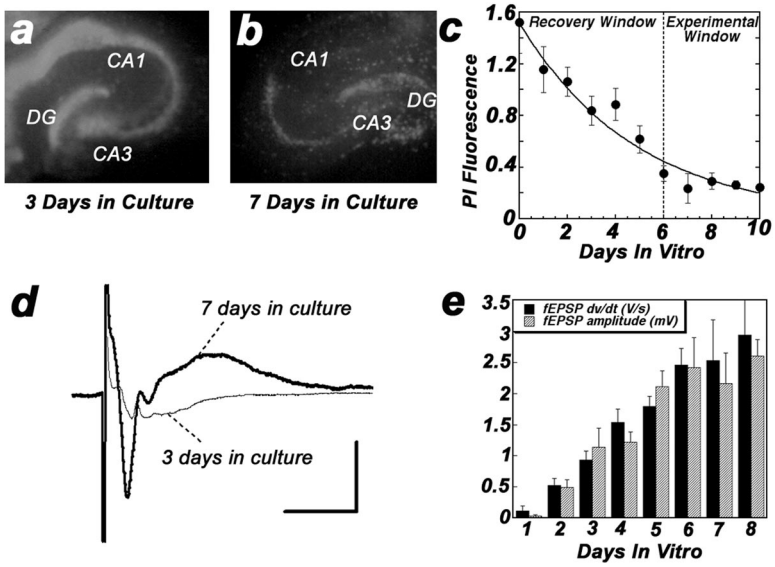

Figure 1. Time course of recovery from damage attributable to slice preparation. a and b, PI fluorescence labeling in hippocampal slice cultures at 3 (a) and 7 (b) DIC. c, Mean±SEM PI fluorescence intensities in CA1 stratum pyramidale over the first 10 DIC (n=11). d, Representative Schaffer collateral-evoked EPSPs recorded 3 and 7 DIC (calibration bars 10 ms/3 mV). e, Mean±SEM recovery of EPSPs dV/dt (V/s; solid bars) and peak amplitude (mV; gray bars) as a function of DIC.

formed on total RNA isolated from hippocampal slice cultures[17] with the Thermoscript RT-PCR system (Gibco BRL). Reaction products were analyzed by electrophoresis on 2% agarose gels. Connexin primers were: Mus Cx36 [5′GAGCAAACGAGAAGATAAGAAG-3′; 3′-CCGCTTCTACATCATCCA-5′] (195 bp)[17] and densitometric assays normalized to 18s mRNA.

Fluorescence Recovery After Photobleaching

Slice cultures were loaded by 45-minute application of carboxyfluorescein diacetate (30 μmol/L). CA1 fields of view were photobleached for 2 minutes using the 488-nm laser line of a confocal microscope (Nikon RCM 8000) and images acquired at 1-minute intervals.

In Vivo Intrauterine HI

Pregnant rats at term (21 days gestation) were anesthetized, decapitated, the abdomen incised, and uterus quickly isolated from blood supply and surrounding tissue. Acute anoxia was induced by immersing the intact uterus in 37°C saline for 12.5 minutes. Surgical survival was 92±5% after 12.5 minutes of birth anoxia. Controls were delivered by cesarean section without additional HI. Blood gases and pH were measured (RapidLab 855; Bayer) from a mixture from cut cord immediately after delivery.

Dissociated Neuronal Cultures and Exposure to Hypoxia

Primary neuronal cultures (<5% glia) were prepared[18] from embryonic day 14.5 C57BL/6 embryos. In 60-mm culture plates, 1.75×10^6 cells were dispersed. To induce hypoxia, cultures were placed in an incubator with 0.5% O_2 (N_2 replacing O_2) for 24 hours (37°C, 5% CO_2).

Results

Delayed Neuronal Death in Organotypic Hippocampal Slice Cultures

Initial studies characterized the time course of recovery from damage attributable to slice culture preparation. Neuronal death in hippocampal principal layers was assessed by PI staining in principal cell layers daily for the first 10 days in culture (DIC; Figure 1a through 1c). PI staining showed significant neuronal death in slice cultures at 1 DIC that progressively decreased during the first 5 DIC ("recovery window"). By 6 to 10 DIC, cell death was at low steady-state levels. Recordings of Schaffer collateral-evoked field excitatory postsynaptic potentials (fEPSPs) revealed a similar time course of functional recovery (Figure 1d). Based on these data, we studied slice cultures during 6 to 10 DIC ("experimental window").

Gap Junction Blocker CBX Reduces OGD-Induced Delayed Neuronal Death in Hippocampal Slice Cultures

Sustained hypoxia and ischemia produce severe and irreversible functional deficits at Schaffer collateral–CA1 synapses in vitro and widespread delayed neuronal death in all hippocampal principal cell layers.[16] Slice cultures were subjected to 45 minutes of 95% N_2/5% CO_2 plus glucose-free medium (OGD), which produced large numbers of PI-positive pyramidal neurons 24 hours later (Figure 2b). Consistent with our hypothesis that gap junctions contribute to delayed neuronal death, CBX (75 μmol/L) added to culture medium 30 minutes before, during, or 60 minutes after OGD markedly reduced delayed death of CA1 pyramidal neurons assessed by PI staining 24 hours later (Figure 2c and 2d). Treatment of control organotypic slice cultures with CBX alone did not detectably alter viability or morphology of slices 24 hours later (data not shown). The time course of PI staining in the first 24 hours after OGD in CA1 stratum pyramidale (Figure 2e) is suggestive of apoptosis, a conclusion reinforced by the generation of nucleosomal DNA fragmentation (Figure 2e) and activation of the apoptosis-triggering enzyme caspase-3 (Figure 2f). In hippocampal slice cultures after OGD, activated caspase-3 protein increased to 192±9% of control values (n=24 slices from 3 littermates; Student's t test; $P<0.005$; control versus OGD).

Consistent with reducing delayed death of CA1 pyramidal neurons, CBX markedly reduced OGD-induced loss of Schaffer collateral synaptic transmission in CA1 stratum radiatum. Figure 2g illustrates these experiments in typical untreated slice cultures, in which OGD caused virtually complete loss of evoked fEPSPs with minimal recovery 24 hours after OGD. In contrast, a second group of hippocampal slices

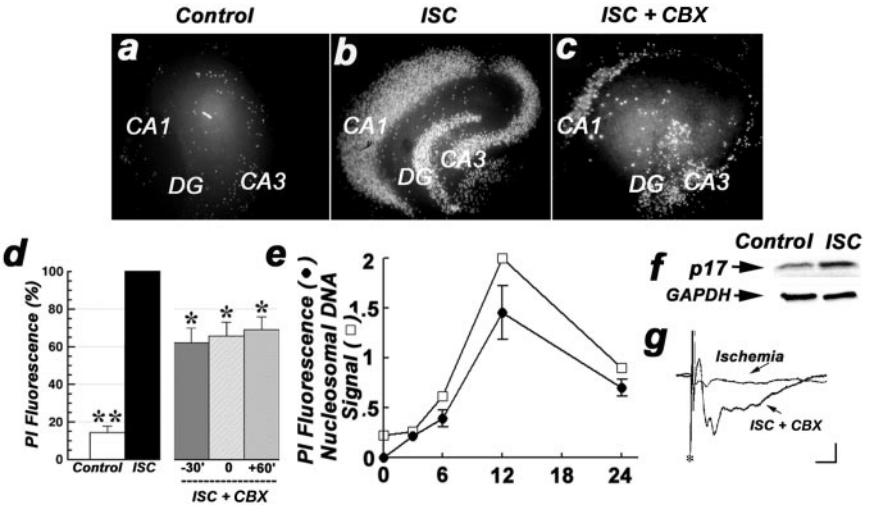

Figure 2. Gap junction blockade protects CA1 pyramidal neurons in organotypic cultures from OGD-induced delayed neuronal death. a, PI fluorescence in a control, nonischemic slice culture. b, PI fluorescence in CA1, CA3, and DG24 hours after OGD in a representative hippocampal slice culture. c, PI fluorescence 24 hours after OGD in a hippocampal slice culture treated with 75 μmol/L CBX 60 minutes after the end of OGD. d, Mean±SEM PI fluorescence in CA1 stratum pyramidale of cultures treated with 75 μmol/L CBX 30 minutes before (−30′), during (0′), or 60 minutes after (+60′) OGD as percentage of OGD treatment alone (n=11 to 13 slice cultures). e, Time course of mean±SEM PI fluorescence (●) and nucleosomal DNA (□) in slice cultures (n=6 per time point) during the first 24 hours after slicing. f, Western blots of active p17 (17 kDa) subunit of caspase-3 from OGD-treated slice cultures 24 hours after OGD (ISC) and normoxic control cultures (Control). g, Schaffer collateral-evoked EPSPs recorded in CA1 stratum radiatum 24 hours after OGD in untreated (Ischemia) and CBX-treated (75 μmol/L applied immediately after OGD; ISC+CBX) slice cultures (calibration bars 10 ms/3 mV).

treated with 75 μmol/L CBX exhibited substantial recovery of evoked fEPSPs (ischemic [ISC]+CBX) after identical 45-minute OGD episodes (CA1 EPSP dV/dt 24 hours after OGD; control [n=6] 2.1±0.32 V/s; CBX [n=6] 0.3±0.1 V/s; Student's *t* test; $P<0.005$).

Fluorescence Recovery After Photobleaching Demonstrates Blockade of Junctional Coupling by CBX

To directly measure the extent of cell–cell coupling before and after OGD, cells were loaded by bath application of the gap junction-permeable fluorescent dye carboxyfluorescein diacetate, then an area of the slice was photobleached with high-intensity light. The rate of reappearance of fluorescence is a function of intracellular diffusion of nonbleached dye from neighboring cells through gap junctions. Figure 3a illustrates areas within stratum pyramidale of field CA1 subjected to fluorescence recovery after photobleaching (FRAP) under control conditions and 24 hours after OGD, with and without CBX pretreatment. The top row illustrates carboxyfluorescein-loaded cells before photobleaching; the middle row, 2 minutes, and the bottom, row 9 minutes after photobleaching. Recovery of fluorescence was significantly more rapid in slices subjected to OGD ($\tau_{ISC}=56.6\pm5$ s; Student *t* test; $P<0.05$) compared with normoxic slices ($\tau_{CON}=117\pm20$ s), whereas number and brightness of cells after initial uptake of dye was not altered, indicating that OGD produced persistent functional upregulation of coupling. Moreover, CBX applied to ischemic cultures 45 minutes before FRAP assay markedly decreased rate of recovery (Figure 3a; ISC+CBX; $\tau_{CARB}=332.6\pm66$ s; Student *t* test; $P<0.05$), demonstrating that FRAP is indeed mediated by

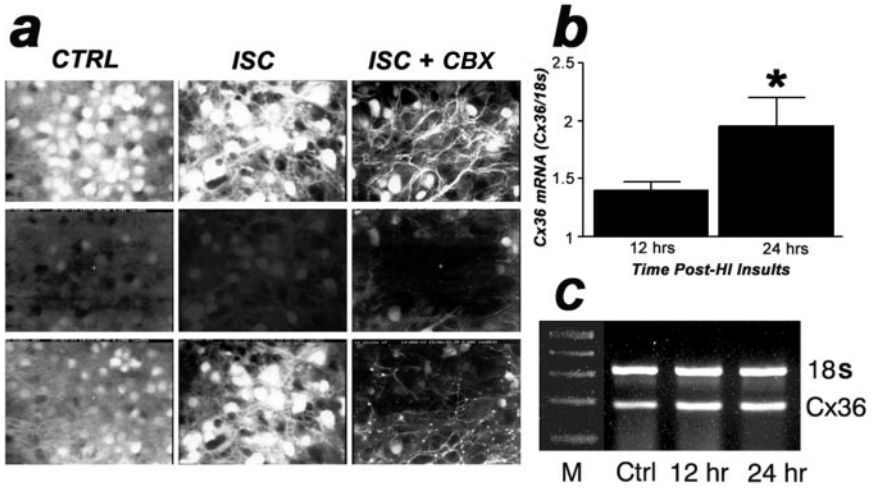

Figure 3. Expression of functional coupling and Cx36 mRNA after OGD. a, FRAP in fields in stratum pyramidale in control (CTRL), OGD alone (ISC), and OGD followed by 75 μmol/L CBX (ISC+CBX) slice cultures before (top row), 2 minutes (middle), and 9 minutes (bottom) after photobleaching. b and c, Semiquantitative RT-PCR assays show increased levels of expression of Cx36 as a function of time. *$P<0.05$.

Reduction in Mortality After HI Insults With CBX Treatment

	Cesarean Section (without HI)	Cesarean Section After HI
pH	7.3±0.1	6.8±0.2 (n=8)
P_{CO_2} (mm Hg)	76±3.5	45±5 (n=8)
Mortality 4 hours after HI	N/A	36.5% (untreated)
		23.5% (CBX-treated)
Mortality 24 hours after HI	N/A	43% (untreated)
		27% (CBX-treated)
Mortality 48 hours after HI	N/A	49.5% (untreated)
		30% (CBX-treated)†
Survival 21 days after HI	N/A	45.5±15% (untreated)
		70±12% (CBX-treated)‡

Fisher exact test (untreated vs CBX-treated HI pups: †P=0.02; ‡P=0.14).

gap junctions. Semiquantitative RT-PCR revealed increased expression of hippocampal Cx36 after OGD (Figure 3b and 3c). These data provide evidence that functional gap junctional coupling is substantially and persistently increased 24 hours after OGD in hippocampal slice cultures and confirm that 75 μmol/L CBX substantially reduces coupling in this preparation.[12]

In Vivo Blockade of Gap Junctions With CBX Reduces Mortality and Delayed Developmental Neuropathology After Perinatal Ischemia

The neuroprotection afforded by CBX in vitro suggests that blockade of gap junction channels, during or even after ischemia, might improve recovery and lessen brain damage in vivo, especially early in development, when neuronal gap junction expression is high.[18] To test this hypothesis, transient intrauterine global HI was produced at term. Across all litters, intrauterine HI resulted in changes in pH, P_{O_2}, and markedly increased mortality (Table). Consistent with a role for gap junctions in intrauterine HI-induced damage, CBX administered immediately after HI (75 mg/kg) ameliorated the long-term developmental impact of perinatal HI (Table).

Consistent with previous reports,[19,20] neuropathologies resulting from intrauterine HI varied between litters, ranging from slowed growth to gross encephalopathy, including marked developmental abnormalities in hippocampus, neocortex, and cerebellum. By postnatal day (P21) 21, 16% of HI rat pups weighed ≈40% less than normoxic and ≈20% less than HI CBX-treated littermates (ANOVA; P<0.005; control 38.5±1 g; HI 23±4 g; CBX-treated HI rats 29.2±3 g). Histopathological analyses of hematoxilin-eosin–stained sections from brains of 5 P9 to P21 rats subjected to perinatal HI compared with controls and CBX-treated littermates revealed hypercellularity in the hilar region of the hippocampal dentate gyrus (DG), a site of late neurogenesis[21] (DG cells/0.015 mm^2 for normoxic P21 animals=11±2; HI=37±7; HI+CBX=13±2; n=16 fields in 5 animals; P<0.001; Figure 4, hippocampus, white arrow). Three of 5 exhibited abnormal cerebellar development with atrophic follia and superficial sulci. Hypercellularity and thickness abnormalities of the external granular layer were also evident (cells/0.05 mm^2 for normoxic animals=44±2.5; HI=58±3; HI+CBX=46±2.5; n=26 fields in 5 animals; P<0.05; EGL thickness in normoxic animals=24.5±3 μm; HI=85±12 μm; HI+CBX=34±4 μm; n=25 fields in 5 animals; P<0.01; Figure 4, cerebellum). Two animals showed cortical laminae disorganization not restricted to primary sensory areas, but also present in associative regions of HI animals. Quantification of cells in layer 5 of somatomotor cortex revealed a mean of 3.4±0.5 dying cells/100 μm^2 in HI versus 0.5±0.1 dying cells/100 μm^2 in normoxic and 1±0.5 dying cells/100 μm^2 in HI+CBX (n=23 fields in 5 animals; P<0.001). Analysis at higher magnification revealed shrinkage of cytoplasm and condensation of the nucleus of pyramidal cells, suggestive of cell damage (Figure 4; neocortex, ISC, white arrows). Three animals showed ventricular dilation (data not shown). Consistent with the hypothesis that gap junctional coupling is a necessary contributor to these long-term consequences, CBX treatment dramatically reduced the extent of histopathological damage in hippocampus (Figure 4; ISC+CBX), neocortex, and cerebellum.

Gap Junction Blockade Prevents Activation of Caspase-3 by Intrauterine HI

To assess effects of HI, and gap junction blockade after HI, on activation of the apoptosis-triggering enzyme caspase-3,

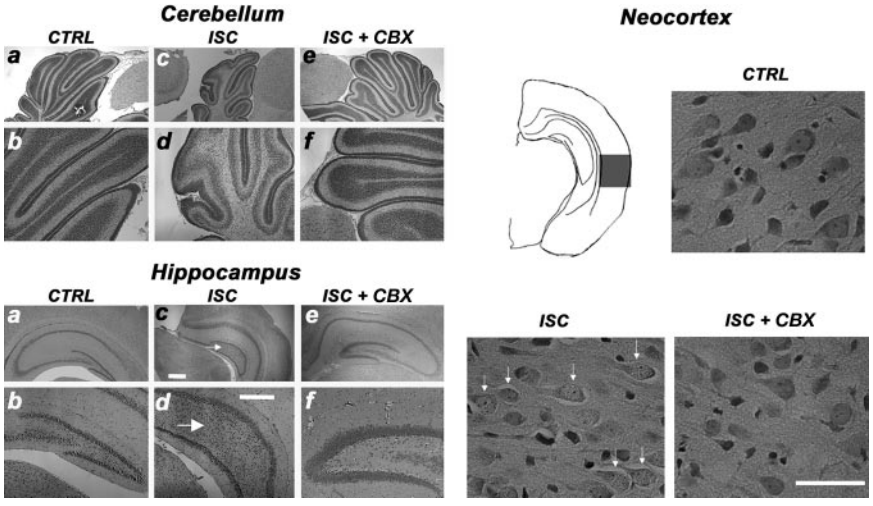

Figure 4. Sections of cerebellum from control (CTRL), HI-treated (ISC), and HI plus CBX–treated (ISC+CBX; 75 mg/kg IP) rats at 21 days of age. HI produced marked reductions in cerebellar size (c) and resulted in granule layer hypertrophy (d) compared with both controls (a and b) and CBX-treated (e and f) littermates. Hippocampus, CTRL, ISC, and ISC+CBX P21 hippocampi. Note the hypercellularity in the dentate hilus after ischemia (arrows, c and d). Neocortex, Sections of neocortex from CTRL, ISC, and ISC+CBX P21 rats. Note the pyknotic neurons with damaged membranes and nuclear shrinkage (ISC, arrows). Bars=500 μm (hippocampus and cerebellum); 20 μm (neocortex).

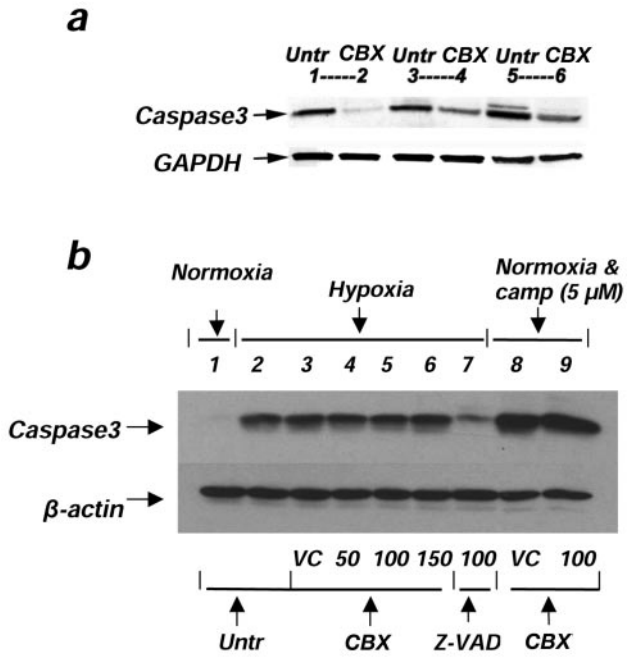

Figure 5. a, Gap junction blockade lessens activation of caspase-3 in P1 brain 24 hours after HI. Activation of caspase-3 was demonstrated by the appearance of the active p17 (17 kDa) subunit 24 hours after HI in Western blots of forebrain from 3 pairs of littermates treated either with intrauterine HI alone (Untr) or HI followed immediately by CBX (CBX; 75 mg/kg IP). b, Accumulation of caspase-3 was induced in cultured neurons by 24 hours of hypoxia (lanes 2 to 7) or camptothecin (lanes 8 and 9). CBX at concentrations of 50 to 150 μmol/L did not alter cleavage of caspase-3. In contrast, 100 μmol/L benzyloxycarbonyl-Val-Ala-Asp-fluoromethyl ketone, a general caspase inhibitor, markedly reduced hypoxia-induced cleavage of caspase-3 (lane 7).

we performed quantitative Western blot assays on newborn brains 24 hours after intrauterine HI (Figure 5a). Consistent with our data from hippocampal slices, activated caspase-3 protein levels were markedly and significantly increased in whole brains from HI-treated newborn rats, an effect largely prevented by CBX treatment immediately after HI. In 3 separate experiments comparing rats subjected to perinatal HI with littermates receiving CBX injections (75 mg/kg IP) immediately after HI, CBX reduced to 43±15% the activation of caspase-3 24 hours after HI (Student's t test; $P \leq 0.05$; band densities HI=683±97 and HI+CBX=302±115).

CBX Does Not Directly Inhibit Caspase-3 Cleavage in Dissociated Neurons

To exclude the possibility that CBX may inhibit cleavage of caspase-3 independent of its blockade on gap junctions, we examined hypoxia and camptothecin-induced accumulation of activated caspase-3 in freshly dissociated neurons in culture (n=2). Application of CBX (0.3 to 300 μmol/L) did not alter hypoxia or camptothecin-induced activation of caspase-3 (Figure 5b). In contrast, the general caspase inhibitor benzyloxycarbonyl-Val-Ala-Asp-fluoromethyl ketone effectively prevented caspase-3 cleavage (Figure 5b).

Discussion

In OGD-treated hippocampal organotypic in vitro slice cultures and intrauterine HI in vivo, the relatively selective gap junction blocker CBX was potently neuroprotective, even when administered 60 minutes after ischemia.

The more rapid recovery of fluorescence we observed after photobleaching in organotypic slice cultures 24 hours after ischemia (Figure 3a) demonstrates that OGD persistently increases coupling in vitro. Although FRAP was measured in the CA1 pyramidal cell layer, neuronal and glial coupling are both likely to contribute to the response to ischemia. These results are consistent with findings in an in vitro trauma model[4] that OGD enhances gap junction coupling and promotes bystander cell killing. Introducing gap junction proteins (connexins) into cell lines has been shown to enhance bystander cell death.[22,23] Pharmacological and antisense blockade of gap junctions in hippocampal slice cultures decreases their vulnerability to traumatic injury[4] and HI,[3] and gap junction blockade has been shown to reduce infarct size after arterial occlusion.[9] Although deletion of some connexins has been reported to augment, not decrease, infarct size in rodent stroke models,[10,24] one cannot easily dissociate effects of reduced coupling from secondary effects of altered blood flow or effects downstream of altered connexin expression. Our study helps clarify these results by showing that a net blockade of gap junctions confers neuroprotection immediately after a perinatal HI insult.

Although studies suggest that the majority of neuronal loss 24 hours after perinatal HI is apoptotic, necrosis can also contribute. DNA fragmentation and caspase activation are hallmarks of apoptosis. Nucleosomal DNA fragmentation began to rise by 3 hours after OGD in slice cultures, with a 20-fold increase by 12 hours; PI fluorescence showed a similar time course. The decrease in nucleosomal signal after 12 hours appears to be attributable to nucleosomal degradation that overtakes the rate of production. The good temporal correlation between these measures suggests an apoptosis-like process is induced by OGD in slice cultures.

Although it remains to be shown directly that activation of caspase-3 by OGD caused eventual neuronal death, the pronounced appearance of p17 subunits in P1 brains preceded delayed neuronal death and neuropathologic changes at 9 and 21 days of age. CBX treatment produced marked, parallel reductions in caspase-3 activation and delayed neuronal death and eventual long-term brain damage but did not directly inhibit caspase-3 cleavage in virtually uncoupled primary cultured neurons, consistent with a causal connection between cell coupling, activation of apoptotic pathways, and neuronal death. Because gap junctions do not pass molecules larger than ≈1 kDa, ions such as Na^+ and Ca^{2+}, and reactive free radicals, are likely candidates to be involved in the spread of damage. Because CBX has been shown to inhibit voltage-gated Ca^{2+} channels and synaptic transmission in the retina,[25] it remains to be determined to which extent a combination of calcium channel blockers with gap junction blockade might be an advantageous therapeutic approach. However, substantial neuroprotection after HI or trauma has been shown to be conferred by selectively reducing connexin expression with antisense.[3,4]

The high rate of survival of newborn rats given CBX intraperitoneally demonstrates that there are centrally effective concentrations of CBX that avoid the well-known cardiac

toxicity of gap junction blockers.[12] Because intrauterine HI makes the entire fetus ischemic, the therapeutic effect of CBX could be on the central nervous system, peripheral organs, or vasculature.

Although in clinical practice this may not matter, our in vitro experiments in isolated neural tissue show that central nervous system gap junction blockade confers direct neuroprotection independent of vasculature or any peripheral structure, indicating significant therapeutic potential of gap junction blockers for the treatment of perinatal HI, which currently has no effective therapy.

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References

1. Perez Velazquez JL, Frantseva MV, Naus CC. Gap junctions and neuronal injury: protectants or executioners? *Neuroscientist*. 2003;9:5–9.
2. Lin JH, Weigel H, Cotrina ML, Liu S, Bueno E, Hansen AJ, Hansen TW, Goldman S, Nedergaard M. Gap-junction-mediated propagation and amplification of cell injury. *Nat Neurosci*. 1998;1:494–500.
3. Frantseva MV, Kokarovtseva, Perez Velazquez JL. Ischemia-induced brain damage depends on specific gap-junctional coupling. *J Cereb Blood Flow Metab*. 2002;22:453–462.
4. Frantseva MV, Kokarovtseva L, Naus CG, Carlen PL, MacFabe D, Perez Velazquez JL. Specific gap junctions enhance the neuronal vulnerability to brain traumatic injury. *J Neurosci*. 2002;22:644–653.
5. Cotrina ML, Kang J, Lin JH, Bueno E, Hansen TW, He L, Liu X, Nedergaard M. Astrocytic gap junctions remain open during ischemic conditions. *J Neurosci*. 1998;18:2520–2537.
6. Homma N, Alvarado JL, Coombs W, Stergiopoulos K, Taffet SM, Lau AF, Delmar M. A particle-receptor model for the insulin-induced closure of connexin43 channels. *Circ Res*. 1998;83:27–32.
7. Wang JM, Hayashi T, Zhang WR, Sakai K, Shiro Y, Abe K. Reduction of ischemic brain injury by topical application of insulin-like growth factor-I after transient middle cerebral artery occlusion in rats. *Brain Res*. 2000;859:381–385.
8. Scheepens A, Sirimanne E, Beilharz E, Breier BH, Waters MJ, Gluckman PI, Williams CE. Alterations in the neural growth hormone axis following hypoxic-ischemic brain injury. *Brain Res Mol Brain Res*. 1999;68:88–100.
9. Rawanduzy A, Hansen A, Hansen TW, Nedergaard M. Effective reduction of infarct volume by gap junction blockade in a rodent model of stroke. *J Neurosurg*. 1997;87:916–920.
10. Siushansian R, Bechberger JF, Cechetto DF, Hachinski VC, Naus CC. Connexin43 null mutation increases infarct size after stroke. *J Comp Neurol*. 2001;44:387–394.
11. Lin JH, Yang J, Liu S, Takano T, Wang X, Gao Q, Willecke K, Nedergaard M. Connexin mediates gap junction-independent resistance to cellular injury. *J Neurosci*. 2003;23:430–441.
12. Rozental R, Srinivas M, Spray DC. How to close a gap junction channel. Efficacies and potencies of uncoupling agents. *Methods Mol Biol*. 2001;154:447–476.
13. Personius KE, Balice-Gordon RJ. Loss of correlated motor neuron activity during synaptic competition at developing neuromuscular synapses. *Neuron*. 2001;31:395–408.
14. Menezes JR, Froes MM, Moura Neto V, Lent R. Gap junction-mediated coupling in the postnatal anterior subventricular zone. *Dev Neurosci*. 2000;22:34–43.
15. Cusato K, Bosco A, Rozental R, Guimaraes CA, Reese BE, Linden R, Spray DC. Gap junctions mediate bystander cell death in developing retina. *J Neurosci*. 2003;23:6413–6422.
16. Reyes M, Reyes A, Opitz T, Kapin MA, Stanton PK. Eliprodil, a non-competitive, NR2B-selective NMDA antagonist, protects pyramidal neurons in hippocampal slices from hypoxic/ischemic damage. *Brain Res*. 1998;782:212–218.
17. Urban M, Rozental R, Spray DC. A simple RT-PCR-based strategy for screening connexin identity. *Braz J Med Biol Res*. 1999;32:1029–1037.
18. Rozental R, Srinivas M, Gokhan S, Urban M, Dermietzel R, Kessler JA, Spray DC, Mehler MF. Temporal expression of neuronal connexins during hippocampal ontogeny. *Brain Res Brain Res Rev*. 2000;32:57–71.
19. Rice JE, Vannucci RC, Brierley JB. The influence of immaturity on hypoxic-ischemic brain damage in the rat. *Ann Neurol*. 1981;9:131–141.
20. Nakajima W, Ishida A, Lange MS, Gabrielson KL, Wilson MA, Martin LJ, Blue ME, Johnston MV. Apoptosis has a prolonged role in the neurodegeneration after hypoxic ischemia in the newborn rat. *J Neurosci*. 2000;20:7994–8004.
21. Altman J, Das GD. Autoradiographic and histological evidence of postnatal hippocampal neurogenesis in rats. *J Comp Neurol*. 1965;124:319–335.
22. Elshami AA, Saavedra A, Zhang H, Kucharczuk JC, Spray DC, Fishman GI, Amin KM, Kaiser LR, Albelda SM. Gap junctions play a role in the 'bystander effect' of the herpes simplex virus thymidine kinase/ganciclovir system in vitro. *Gene Ther*. 1996;3:85–92.
23. Shinoura N, Chen L, Wani MA, Kim YG, Larson JJ, Warnick RE, Simon M, Menon AG, Bi WL, Stambrook PJ. Protein and messenger RNA expression of connexin43 in astrocytomas: implications in brain tumor gene therapy. *J Neurosurg*. 1996;84:839–845.
24. Oguro K, Jover T, Tanaka H, Lin Y, Kojima T, Oguro N, Grooms SY, Bennett MV, Zukin SR. Global ischemia-induced increases in the gap junctional proteins connexin 32 (Cx32) and Cx36 in hippocampus and enhanced vulnerability of Cx32 knock-out mice. *J Neurosci*. 2001;21:7534–7542.
25. Vessey JP, Lalonde MR, Mizan HA, Welch NC, Kelly ME, Barnes S. Carbenoxolone inhibition of voltage-gated Ca channels and synaptic transmission in the retina. *J Neurophysiol*. 2004;92:1252–1256.