Ischemia and Ischemic Tolerance Induction Differentially Regulate Protein Expression of GluR1, GluR2, and AMPA Receptor Binding Protein in the Gerbil Hippocampus

GluR2 (GluR-B) Reduction Does Not Predict Neuronal Death

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Background and Purpose—Postischemic delayed neuronal death (DND) of hippocampal CA1 neurons has been suggested to occur as a result of formation of calcium-permeable \( \alpha \)-amino-3-hydroxy-5-methyl-4-isoxazole propionic acid (AMPA) receptors lacking the GluR2 subunit (GluR2 hypothesis). DND can be prevented by a short tolerance-inducing ischemic period. The present study was designed to assess whether postischemic protein levels of GluR2 predict neuronal death. Additionally, the role of AMPA receptor binding protein (ABP) was investigated with respect to neuronal death or survival.

Methods—Postischemic protein expression of GluR1, GluR2, and ABP was analyzed in 3 experimental paradigms of transient global ischemia with the use of subunit-specific antisera and semiquantitative densitometric evaluation. Gerbils were subjected (1) to a 5-minute ischemic period resulting in DND of CA1 neurons; (2) to a 2.5-minute period of ischemia mediating tolerance induction; and (3) to 5 minutes of ischemia in the ischemia-tolerant state (2.5+5 minutes of ischemia 4 days apart).

Results—The major finding was that GluR2 protein levels were significantly downregulated in neuronal subpopulations destined to survive, ie, in CA1 principal neurons after ischemic tolerance induction and in the ischemia-tolerant state, as well as in CA3 neurons after a 5-minute period of ischemia. ABP expression remained unaffected.

Conclusions—Our results modify the GluR2 hypothesis in that postischemic GluR2 reduction also occurs in hippocampal CA1 and CA3 principal neurons without subsequent neuronal death. ABP is obviously not involved in mechanisms of DND or ischemic tolerance induction. (Stroke. 2002;33:1093-1100.)

Key Words: brain ischemia ■ immunohistochemistry ■ ischemic preconditioning ■ receptors, AMPA ■ gerbils

Transient cerebral forebrain ischemia of only 5 minutes’ duration causes selective and delayed neuronal death (DND) of hippocampal CA1 neurons in the gerbil brain. These highly vulnerable CA1 neurons can be protected against irreversible ischemic damage by a preconditioning stimulus, eg, a short sublethal period of ischemia. The precise molecular mechanisms of both phenomena, DND and endogenous neuroprotection of CA1, however, are still under discussion. An increase of cytosolic free calcium caused by neurotoxic activation of receptor- or voltage-operated ion channels is thought to play a major role in DND. Recent experimental evidence points to an additional or alternative zinc neurotoxicity after cerebral ischemia. Since pharmacological blockade of calcium-permeable \( N \)-methyl-\( d \)-aspartate (NMDA) receptors does not prevent postischemic degeneration of CA1 neurons, interest has focused increasingly on \( \alpha \)-amino-3-hydroxy-5-methyl-4-isoxazole propionic acid (AMPA) receptors, another major subtype of glutamate receptors. Recent evidence suggests that AMPA receptors are tetramers that can be assembled from 4 different subunits, GluR1 to GluR4 (GluR-A to GluR-D). They are impermeable to calcium ions as long as at least 1 GluR2 subunit in its edited form is present. Previous work demonstrated that GluR2 editing is not altered by global ischemia and is unlikely to contribute to neuronal degeneration. The observation that 1 GluR2 subunit can determine the calcium permeability of AMPA receptors in conjunction with a postischemic downregulation of GluR2 mRNA levels at 24 hours led to the so-called GluR2 hypothesis, suggesting a contribution of calcium-permeable AMPA receptors to DND.

AMPA receptor binding protein (ABP) is a recently cloned novel component of the postsynaptic density that binds to the C termini of GluR2 and GluR3 subunits via PDZ domains and is involved in the regulation of AMPA receptor function by dynamically regulating postsynaptic localization and clus-
tering of AMPA receptors. To address the question of whether ABP is also involved in mechanisms of DND or ischemic tolerance induction, interest in the present study also focused on a possible link between the kinetics of GluR2 protein expression and changes in ABP expression.

Materials and Methods

Animal Experiments
Experiments were performed on adult male Mongolian gerbils (Meriones unguiculatus; weight, 70 to 80 g) obtained from Charles River Deutschland (Sulzfeld, Germany). Animals had free access to food and water before experiments. Gerbils were subjected to transient forebrain ischemia by bilateral occlusion of the common carotid artery. Ischemic tolerance was induced according to the protocol of Kirino et al with minor modifications. Anesthesia was achieved with a mixture of 30% O2, 70% N2O, and 1.5% halothane. Three experimental groups of animals were investigated. One group was subjected to a single 5-minute period of ischemia, resulting in DND of CA1 neurons. The second group was subjected to a single tolerance-inducing 2.5-minute period of ischemia, and a third group was subjected to 5 minutes of ischemia in the ischemia-tolerant state (2.5–5 minutes of ischemia 4 days apart, a paradigm that results in survival of almost all CA1 neurons). Sham-operated control gerbils were subjected to anesthesia and all surgical procedures, except clamping of the carotid arteries. Animals were killed by transcardiac perfusion under deep ether anesthesia. Heparin (90 IU) was given via the left ventricle before washout of blood vessels with isotonic saline. Brains were perfusion-fixed with 4% (wt/vol) paraformaldehyde solution, removed, and postfixed overnight in the same fixative before vibratome sectioning. Postischemic expression of GluR1 and GluR2 subunit protein was investigated in sham-operated gerbils and in all experimental groups after recirculation intervals of 8, 24, 48, and 96 hours (n=4 to 9). All procedures were performed according to the guidelines of the German animal protection law.

Neuropathological Evaluation
Neuronal cell densities within the hippocampal pyramidal layers were quantitatively assessed after labeling neurons with an antibody against the neuronal marker protein NeuN as previously described. Six groups of gerbils were investigated at 96 hours after sham procedure or reperfusion: untreated control gerbils (n=4), gerbils subjected to a single (n=5) or repetitive (n=3) sham operation, and gerbils subjected to 2.5 minutes (n=8), 2.5–5 minutes (n=4), or 5 minutes (n=6) of ischemia. Hippocampal subfields CA1 and CA3 of both hemispheres were scanned at a magnification of ×300. Two sets of 3 adjacent regions per area (strictly localized within the pyramidal cell layer of CA1 or CA3) per hemisphere were recorded, averaged, and expressed as mean cell number per square millimeter (neuronal density). All data were statistically analyzed with the use of the general statistics module of Analyze-it for Microsoft Excel (Analyze-it Software, Ltd). Values were expressed as mean±SEM. Significant group effects were confirmed by ANOVA and Bonferroni error protection with a significance level at P<0.05.

Immunohistochemistry
Immunohistochemistry was performed with antibodies against GluR1 protein (obtained from Chemicon International Inc), GluR2 protein (kindly provided by R. Wenthold), and ABP (kindly provided by E.B. Ziff), which were generated in rabbits immunized with bacterially expressed fusion proteins. Antibodies against the neuronal marker protein NeuN as previously described were confirmed by ANOVA and Bonferroni error protection at P<0.05.

Results

Neuropathological Evaluation
Immunohistochemical analysis of NeuN-stained neurons in hippocampal subfields CA1 and CA3 revealed no significant differences between untreated control gerbils and gerbils subjected to a single or repetitive sham operation in both CA1 and CA3 (Table). A single 5-minute period of ischemia caused a significant reduction of neuronal cell density in the hippocampal CA1 subfield to 25% at 96 hours after reperfusion compared with sham-operated gerbils, whereas CA3 was unaffected (Table). Both a single tolerance-inducing 2.5-minute period of ischemia and a 5-minute period of ischemia in the ischemia-tolerant state led to focal neuronal loss in CA1 of some animals (not shown). This, however, did not result in a significant reduction of neuronal cell density in the hippocampal CA1 subfield at 4°C. The primary antibodies were diluted 1:100 (GluR1), 1:200 (GluR2), and 1:250 (ABP). Then slices were washed with PBS and 0.2% Triton X-100, followed by an incubation period of 30 minutes at room temperature with a secondary biotinylated anti-rabbit IgG antibody. After a rinse with PBS and 0.2% Triton X-100, immunoreactivity was visualized by the avidin-biotin complex method (Vectastain, Vector Laboratories). Sections were developed in 0.02% diaminobenzidine with 0.02% hydrogen peroxide. The reaction product was intensified by addition of 0.02% cobalt chloride and nickel ammonium sulfate. Omitting the primary antiserum in a subset of control slides resulted in no immunostaining (not shown).

For semiquantitative analysis of receptor protein expression, hippocampi were investigated by optical densitometry as previously described with minor modifications. All sections were examined at a final magnification of ×40 with a Zeiss Axioskop microscope. Images were scanned in equal light conditions with a DMC video camera (Polaroid). From hippocampal subfields CA1 and CA3, 4 regions of interest (ROI) in the pyramidal layer (GluR1 and GluR2) or in dendritic layers (ABP), respectively, were selected on the monitor. ROIs were rectangular areas of 0.01 mm² (0.05×0.2 mm). Optical density of immunoreactivity within the ROIs was automatically determined with AIS imaging research software (Imaging Research Inc). The optical density of the corpus callosum was used as reference value for background staining (OD ref) and subtracted from total optical density in the ROI (OD ROI), resulting in specific optical density (OD sp). Specific immunolabeling was calculated as the ratio OD ROI/OD ref. Values (in percentages) are expressed as mean±SEM. Statistical analysis was performed with the use of the general statistics module of Analyze-it for Microsoft Excel (Analyze-it Software, Ltd). Significant group effects were confirmed by ANOVA and Bonferroni error protection with a significance level at P<0.05.

<table>
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<tr>
<th>Group</th>
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<th>CA3</th>
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<td>2618±163</td>
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<td>3133±208</td>
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<td>5177±164</td>
<td>2854±64</td>
</tr>
<tr>
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<td>4215±508</td>
<td>3299±123</td>
</tr>
<tr>
<td>5-min ischemia</td>
<td>6</td>
<td>1292±726*</td>
<td>2815±142</td>
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</table>

Values are mean±SEM, expressed as neuronal density per square millimeter.

*Values were significantly lower compared with controls, sham-operated gerbils, and gerbils subjected to 2.5- or 2.5–5-minutes ischemia (P<0.05, ANOVA and Bonferroni error protection).
these experimental groups (Table). Again, CA3 remained unaffected (Table).

**Immunohistochemistry (GluR1, GluR2, and ABP)**

**Five Minutes of Ischemia**

Prominent immunoreactivity for both GluR1 and GluR2 was present in the pyramidal layers of hippocampal subfields CA1 and CA3 in sham-operated gerbils (Figure 1). In CA1, GluR1 immunoreactivity was unchanged up to 48 hours of reperfusion and became restricted to a few scattered surviving interneurons at 96 hours (Figures 1 and 2). GluR1 immunoreactivity in CA3 remained unchanged at all time points investigated (Figures 1 and 2). Immunostaining for GluR2 in CA1 continuously decreased after ischemia, reaching significance at 48 and 96 hours. However, GluR2 immunoreactivity was not completely abolished 96 hours after reperfusion and yet was detectable in damaged shrunken CA1 neurons. In CA3, GluR2 immunoreactivity was significantly reduced between 8 and 48 hours, reattaining control levels at 96 hours after recirculation (Figures 1 and 2).

In sham-operated gerbils, ABP immunoreactivity in CA1 and CA3 was only weak in the pyramidal layer but was prominent in dendritic layers (Figure 1). Postischemic ABP immunoreactivity in CA1 was unaffected up to 48 hours after reperfusion but was significantly reduced at 96 hours (Figures 1 and 2). In CA3, no significant alterations of ABP protein expression were detectable (Figures 1 and 2).

**Tolerance-Inducing Ischemia (2.5 Minutes)**

Again, in sham-operated gerbils GluR1 immunoreactivity (not shown) and GluR2 immunoreactivity were prominent in neurons of the pyramidal layers of hippocampal subfields CA1 and CA3. A single 2.5-minute period of ischemia caused no alterations of the GluR1 immunoreactivity pattern in both CA1 and CA3 (Figure 2). GluR2 immunoreactivity in CA1, however, was transiently but significantly reduced at 24 hours (Figures 2 and 3). At 96 hours after reperfusion, GluR2 levels corresponded to those of sham-operated animals (Figures 2 and 3). Staining intensity of GluR2 immunoreactivity in CA3 was slightly but not significantly reduced between 24 and 96 hours (Figures 2 and 3).

ABP protein expression after a tolerance-inducing period of ischemia was not significantly altered in CA1 and CA3 at all time points investigated (Figures 2 and 3).

**Five Minutes of Ischemia in the Ischemia-Tolerant State (2.5/5 Minutes of Ischemia 4 Days Apart)**

In gerbils subjected to repetitive sham operation, the staining pattern and intensity for GluR1 and GluR2 corresponded to those of gerbils subjected to a single sham operation (not shown). GluR1 immunoreactivity in both CA1 and CA3 exhibited no significant alterations at all time points investigated (Figure 2). GluR2 immunoreactivity, however, showed a significant reduction at 8 hours in CA1 and was only slightly but nonsignificantly decreased at 8 and 24 hours in CA3 (Figures 2 and 4). As after the preconditioning ischemic period, ABP immunoreactivity in the ischemia-tolerant state was unchanged in CA1 and CA3 at all time points investigated (Figures 2 and 4).

**Discussion**

Our study corroborates the GluR2 hypothesis in that, compared with GluR1, a 5-minute period of global ischemia severe enough to cause DND of CA1 pyramidal cells was associated with a continuous and selective decrease of GluR2 protein expression, which first reached significance at 48 hours after recirculation. This is a remarkable finding for several reasons. (1) In situ hybridization studies addressing postischemic GluR2 expression in CA1 yielded contradictory results: 4 studies showed a preferential decline of GluR2 mRNA in highly vulnerable CA1 neurons, whereas 3 other studies observed an unchanged ratio between the mRNAs encoding GluR1 and GluR2 subunits.

In contrast to global cerebral ischemia in rats with at least partially maintained postischemic protein synthesis in vulnerable CA1 neurons, total protein synthesis in the gerbil...
A model of transient cerebral ischemia is almost completely and irreversibly inhibited in CA1. Despite this overall protein synthesis failure, however, heat shock protein 72 mRNA has been shown to be preferentially translated in postischemic gerbil hippocampal CA1 sector. Nevertheless, the translational deficit in CA1 neurons may have a profound impact on the respective protein expression pattern, and mRNA data alone do not predict postischemic abundance of a particular encoded protein. (3) On the protein level, Optiz and colleagues, using the same antibody as in the present study, first detected reduced postsischemic GluR2 expression in CA1 neurons at 72 hours of reperfusion immunohistochemically and at 60 hours in microdissected CA1 sectors by immunoblotting. These data are somewhat at variance with our results. Ischemic damage of medial CA1 principal neurons precedes that of lateral pyramidal cells and frequently already manifests morphologically at 72 hours after reperfusion. At the same time point, nuclear DNA fragmentation is also

Figure 2. Semiquantitative assessment of postsischemic hippocampal GluR1, GluR2, and ABP immunoreactivity in various experimental paradigms. After a single 5-minute period of ischemia, GluR2 immunoreactivity is progressively reduced in CA1 compared with GluR1 and ABP but first reaches significance immediately before DND (a). In CA3, GluR2 immunoreactivity is significantly decreased between 8 and 48 hours but has nearly reattained control values at 96 hours (b). A single 2.5-minute tolerance-inducing ischemia significantly and selectively reduces GluR2 immunoreactivity in CA1 after 24 hours (c), whereas GluR1 and ABP are unaffected in both CA1 (c) and CA3 (d). Similarly, in the ischemia-tolerant state, GluR2 is transiently reduced at 8 hours (e), whereas GluR1 is nonsignificantly decreased and ABP remains unchanged in CA1 (e) and CA3 (f). OD-sp indicates specific optical density; OD-tot, total optical density. *Significant (P<0.05, ANOVA and Bonferroni error protection).
detectable in the medial part of CA1.43 Thus, in agreement with these observations, 72 hours seems to be a critical time point beyond the threshold for incipient evidence of neuronal degeneration.

The validity of the GluR2 hypothesis has meanwhile been restricted by the original proponents to specific neuronal subpopulations. GluR2 knockdown experiments by antisense treatment led to a reduction of GluR2 in granule cells of the dentate gyrus but did not trigger granule cell degeneration, whereas neurons of CA1 and to a lesser extent neurons of CA3 underwent cell death,44 thus indicating a different sensitivity of neuronal subpopulations to GluR2 downregulation. Our present findings modify the GluR2 hypothesis in that diminished abundance of the GluR2 subunit in CA3 neurons after ischemia of 5 minutes’ duration (Figures 1 and 2) and even in the same neuronal subpopulation, ie, hippocampal CA1 neurons (at 24 hours after a single 2.5-minute period of ischemia and at 8 hours in the ischemic tolerant state), is not necessarily followed by cell death (Figures 2, 3, and 4). Similarly, Friedman and colleagues,36 using the rat model of global cerebral ischemia, recently demonstrated that neurons survive because they permanently express calcium-permeable AMPA receptors, whereas only neurons that suddenly have to cope with a high calcium influx through GluR2 lacking AMPA receptors undergo cell death. However, a recent study by Tóth and McBain51 demonstrated that interneurons of the stratum lucidum constitutively possess calcium-permeable AMPA receptors but still die after transient ischemia or kainate-induced seizures.52,53 In general, the notion that postischemic calcium influx through ion- or voltage-gated calcium channels with a concomitant increase of cytosolic free calcium inevitably results in irreversible cell damage has been reexamined: Recent in vitro work indicates that depletion of endoplasmic reticulum calcium stores and/or elevated calcium uptake in mitochondria may cause neuronal death, irrespective of free cytosolic calcium concentration.54–56

In regard to the regulation of AMPA receptor subunit expression after a preconditioning ischemic stimulus, to our knowledge there are only 3 studies, all from the laboratory of Diemer.35,45,57 Using in situ hybridization, these authors demonstrated that postischemic GluR2 expression in hippocampal CA1 neurons remains unchanged, whereas quantitative polymerase chain reaction analysis yielded a significant upregulation of GluR2 mRNA.35 The different PCR results are explained by polyadenylation of preexisting GluR2 mRNA, which in turn is thought to enhance synthesis of

![Figure 3. Hippocampal immunostaining for postischemic GluR2 and ABP immunoreactivity after a tolerance-inducing 2.5-minute ischemic period. After tolerance induction, GluR2 immunoreactivity (left) in CA1 is transiently reduced at 24 hours. In CA3, a moderate but nonsignificant reduction is evident at 24 hours (see Figure 2). Note that ABP immunoreactivity (right) is unchanged at all time points investigated. Bar=500 µm.](http://stroke.ahajournals.org/)

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GluR2 protein, as reflected by a significant increase of GluR2 protein expression at 24 hours after preconditioning in microdissected CA1 regions assessed by immunoblotting. It cannot be excluded that the discrepancy with our immunohistochemical data, demonstrating reduced GluR2 protein expression in CA1 at 24 hours after tolerance induction (Figures 2 and 3), is due to an interspecies variation. More importantly, however, immunolabeling experiments by Western blotting do not distinguish between neuronal and nonneuronal GluR2 protein. In vitro, hippocampal astrocytes show GluR2 immunoreactivity, which may contribute to total GluR2 abundance in immunoblots. Moreover, homogenates do not reflect GluR2 subunit abundance of individual cells. To clarify this point, further experiments using in situ detection methods of GluR2 protein expression need to be performed in the preconditioned rat hippocampus.

In conclusion, in agreement with the GluR2 hypothesis, our data demonstrate that CA1 neurons destined to die after global ischemia of 5 minutes' duration exhibit reduced levels of GluR2 protein expression immediately before cell death. However, posts ischemic GluR2 protein levels were also substantially and significantly reduced in neuronal subpopulations destined to survive (in CA3 neurons after 5 minutes of ischemia and in CA1 neurons after induction of ischemic tolerance and in the ischemia-tolerant state), thus further restricting and modifying the GluR2 hypothesis. ABP, a novel AMPA receptor anchoring protein, appears to be unrelated to posts ischemic neuronal death or survival.

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