Histamine H₂-Receptor Antagonist Ranitidine Protects Against Neural Death Induced by Oxygen-Glucose Deprivation

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Background and Purpose—Administration of histamine receptor antagonists has been reported to produce contradictory results, either reducing or increasing neural damage induced by ischemia. In this study, we investigated the neuroprotective effects of histamine H₂-receptor antagonists in an “in vitro” model of ischemia.

Methods—Cultured rat brain cortical neurons were exposed to oxygen-glucose deprivation (OGD) in the presence or absence of different histaminergic drugs. Cell viability was measured by 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide reduction assay. Necrosis and apoptosis were quantified by staining cells with propidium iodide and Hoechst 33258. Caspase 3 activation was determined by immunocytochemistry and Western blot.

Results—Pretreatment with H₂ antagonists effectively reduced neuronal cell death induced by OGD. Ranitidine decreased the number of necrotic and apoptotic cells. Caspase 3 activation and alteration of the neuronal cytoskeleton were also prevented by ranitidine pretreatment. The neuroprotective effect of ranitidine was still evident when added 6 hours after OGD.

Conclusions—H₂-receptor antagonists protected against OGD-induced neuronal death. Ranitidine attenuated cell death even when administered after OGD. These data suggest that this drug, which is currently used for the treatment of gastric ulcers, may be useful in promoting recovery after ischemia. (Stroke. 2004;35:2396-2401.)

Key Words: apoptosis / cerebral ischemia / neuronal death / stroke

Cerebral ischemia triggers a sudden and severe necrotic cell death and a delayed neuronal degeneration with apoptotic features. The major cause of cellular injury is thought to be excess glutamate release mainly caused by the reverse function of its transporters and the consequent overactivation of glutamate receptors. In addition, there are other factors, such as cytokines or other released neurotransmitters, that may modulate the ischemic lesion.

Histamine (HA) plays an important role as a neurotransmitter and as a neuromodulator in the mammalian brain under normal and pathological conditions. During the past decade, the histaminergic system has been implicated in the modulation of cell death in brain disorders. However, the exact mechanisms underlying HA action on ischemia-induced damage have not yet been fully defined. In this respect, it has been reported that activation of HA H₂-receptors leads to excitatory effects through a blockade of calcium-dependent potassium channels and the modulation of hyperpolarization-activated cation channels. Also, some reports have described that HA could positively modulate N-methyl-D-aspartate (NMDA) receptors, which are believed to mediate most of the ischemic-dependent neuronal injury.

HA receptor blockage in ischemia has provided contradictory results. Intraperitoneal administration of HA H₂-receptor antagonists decreases brain edema formation after a common carotid artery occlusion. In contrast, there are some reports that describe adverse effects of these compounds. HA H₂-receptor blockage in cerebral ischemia in gerbil has been reported to enhance neuronal damage. Moreover, Otsuka et al reported that this aggravating effect was associated with a facilitation of catecholamine metabolism in the rat. On the other hand, HA H₁-receptor antagonists attenuated the ischemia-induced decrease in glucose metabolism in rat hippocampal slices.

In this context, the aim of this study was to explore the possible role of HA receptor antagonists on cell death in an in vitro model of cerebral ischemia on the basis of oxygen-glucose deprivation (OGD) exposure. We show here that pretreatment and post-treatment with HA H₂-receptor antagonists reduces cell death and also prevents caspase 3 activation.

Materials and Methods

Chemicals
Ranitidine, HA, propidium iodide (PI) and 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyl tetrazolium bromide (MTT) were provided by...
Sigma-Aldrich. Amantidine and tiotidine came from Tocris. Hoechst 33258 was obtained from Molecular Probes. [$^3$H]HA (51 Ci/mmol) was purchased from Amersham Biosciences. All other reagents came from Merck.

**Antibodies**

The antibody against procaspase 3 (H-277) was from Santa Cruz Biotecnology (Santa Cruz, Calif). The antibody against cleaved caspase 3 was from Cell Signaling (Beverly, Mass). Anti-microtubule-associated protein-2 (MAP-2) was from Chemicon (Temecula, Calif). The antithistidine decarboxylase was from AbCys. Secondary antibodies conjugated with fluorescein or Texas Red were from Jackson ImmunoResearch (West Grove, Pa). Horseradish peroxidase anti-rabbit secondary antibodies and anti-α-tubulin were from Transduction Biolabs (Bedford, Mass).

**Cell Cultures**

Primary cultures of mixed rat brain cortical cells containing neurons and glia were prepared as described, with modifications, from 40 fetal Wistar rats (Servei d’Establulli de la Universitat Autònom de Barcelona, Barcelona, Spain) at 17 days of gestation. Dissociated cells were plated at a density of 3 x 10⁶ cells/cm² in basal medium Eagle (BME) supplemented with 5% FCS, 5% horse serum, 50 U/mL penicillin, 50 μg/mL streptomycin, 2 μmol/L glutamine, and 10 mmol/L glucose and plated onto poly-L-lysine precoated wells. Cells were kept at 37°C, 100% humidity, and in a 95% air/5% CO₂ atmosphere for 7 days in vitro (DIV), when the plating medium was replaced by BME, supplemented as above without FCS and with 10% horse serum containing 10 μmol/L cytosine arabinoside. All experiments were performed with mature cultures (13 to 14 DIV). The procedures followed were in accordance with guidelines of the Comissió d’Ètica en l’Experimentació Animal i Humana of the Universitat Autònoma de Barcelona.

**Oxygen-Glucose Deprivation**

Cultures were deprived of oxygen and glucose as described with modifications. The culture medium was replaced by a glucose-free Earle’s balanced salt solution (BSS) with the following composition (in mmol/L): 116 NaCl, 5.4 KCl, 0.8 MgSO₄·7H₂O, 1 NaH₂PO₄·2H₂O, 26.2 NaHCO₃, 0.01 glycine, 1.8 CaCl₂·2H₂O, and pH 7.4, which was previously saturated with 95% N₂/5% CO₂ at 37°C. Cultures were then placed in an airtight incubation chamber (CBS Scientific) equipped with inlet and outlet valves and were equilibrated for 15 minutes with a continuous flux of gas (5% CO₂/95% N₂). The chamber was then sealed and placed into a humidified incubator at 37°C for 60 minutes. OGD was terminated by removing the cultures from the airtight chamber, replacing the medium, and returning cells to the normoxic conditions. Control sister culture plates were exposed to oxygenated BSS containing 5.5 mmol/L glucose in normoxic conditions during the same time period as the OGD cultures. When used, the histaminergic drugs were present in the BSS media from 20 minutes before OGD until the end of the experiment. In a set of experiments, the H₂-receptor antagonist ranitidine was added to the culture medium 3 or 6 hours after OGD exposure, until the end of the experiment.

**Cell Viability**

Cell viability was monitored by the colorimetric MTT assay as described. Results were expressed as the percentage of viable cells in OGD-exposed plates compared with control normoxic plates.

**Fluorescent Analysis of Necrosis and Apoptosis**

Cells were stained with PI and Hoechst 33258. PI (10 μmol/L) was added to cultures 12 to 16 hours after OGD. To perform the staining with Hoechst 33258, cells were fixed in ice-cold 4% paraformaldehyde and then incubated for 10 minutes at room temperature with 1 μg/mL Hoechst 33258. Cells were analyzed under a nonconfocal fluorescent Leica microscope. Because Hoechst 33258 stains all nuclei and PI stains the nuclei of cells with disrupted plasma membrane, nuclei of viable, necrotic, and apoptotic cells were observed as blue intact nuclei, red round nuclei, and fragmented (or condensed) nuclei, respectively. Cells were counted by a blinded investigator from ≥3 independent experiments. In each experiment, >600 cells were examined in random fields from ≥3 culture wells for each condition. Our cultures showed ~10% of apoptotic and 5% of necrotic cells under basal conditions (data not shown).

**HA Release Determination**

Cultures were incubated for 1 hour at 37°C with BSS containing 5 μmol/L of a mixture of radiolabeled and unlabeled HA. Cells were then rinsed to eliminate the extracellular [$^3$H]HA, and BSS was added for 20 minutes (pre-OGD). OGD was then performed as indicated above. After OGD, BSS was added to cultures for 20 minutes (post-OGD). Two 10-minute samples of BSS were collected from the pre-OGD period together with the BSS from normoxic and OGD-treated cells. Radioactivity was measured, and released HA was calculated taking into account the specific activity in the incubation mixture. The amount of [$^3$H]HA released during OGD was expressed as a percentage over pre-OGD samples.

**Immunohistochemistry**

Cells were plated on BIOCART 8-well culture slides (Becton and Dickinson) and fixed in 4% paraformaldehyde in Tris-buffered saline (TBS; 100 mmol/L Tris, 0.9% NaCl, pH 7.6) for 1 hour at 4°C. After washing, cells were blocked for 1 hour in TBS-Tween 20 0.1% containing 5% BSA and then incubated overnight at 4°C with the primary antibodies against the active form of caspase 3, (diluted 1:50 in blocking buffer) and the cell-specific marker for neurons, MAP-2 (1:1000). Cells were washed with TBS-Tween 0.1% and then incubated with the appropriate secondary antibodies conjugated with fluorescein isothiocyanate or tetramethylrhodamine B isothiocyanate (1:500) in blocking buffer. Culture slides were then mounted and the cells observed under epifluorescence.

**Immunoblotting**

Cell culture extracts were prepared by lysis in Mammalian Protein Extraction Reagent (M-PER; Pierce). Protein content was determined by the Bradford method. A total of 25 μg of protein was resolved on a 15% SDS-PAGE gel and transferred onto Hybond-P (Amersham Biosciences) polyvinylidene difluoride membranes. Blots were blocked with 5% BSA in TBS containing 0.1% Tween 20 and incubated overnight at 4°C in a blocking buffer containing primary antibodies against caspase 3 (1:1000), MAP-2 (1:1000), histidine decarboxylase (1:5000), or α-tubulin (1:10.000). Blots were then incubated with horseradish peroxidase–conjugated secondary antibodies (1:10 000) in the blocking buffer and developed using the Super Signal West Pico Chemiluminescent Substrate method (Pierce).

**Statistical Analysis**

Statistical significance was determined by 1-way ANOVA followed by Tukey multiple comparison test. A value of $P<0.05$ was considered statistically significant.

**Results**

**OGD-Induced Cell Death and HA Release in Cortical Cell Cultures**

We initially established that 75 minutes of OGD exposure induced ~50% of cell death (Figure 1A). Accordingly with previous reports, astrocyte viability was not affected by this period of OGD, as assessed in a pure astroglial culture (data not shown). OGD induced an increase in HA release (≈30%
over normoxic cultures; Figure 1B), whereas protein levels of histidine decarboxylase were not altered (Figure 1B, inset).

Effect of HA H2-Receptor Drugs on OGD-Induced Neuronal Cell Death

When cultures were exposed to OGD in the presence of HA or the H2-agonist amphetamine, cell death was increased up to 75% and 35% over control, respectively (Figure 2). Pretreatment with the H2 antagonists ranitidine, cimetidine, and tiotidine reduced OGD-induced neuronal death (Figure 2).

Identical results were obtained when cell viability was assessed 48 hours after OGD exposure (data not shown). In preliminary experiments, we found that 100 μM ranitidine was the minimal concentration needed to have the maximal reduction in OGD-mediated cell death. Similar results were obtained with other H2-antagonists tested (data not shown). None of the tested antagonists altered the basal rate of cell death.

Effect of Ranitidine on OGD-Induced Necrosis and Apoptosis

To better characterize the effects of ranitidine on OGD-induced neuronal cell death, PI and Hoechst 33258 were added to cultured neurons exposed to OGD in the presence or absence of ranitidine. Twenty-four hours after OGD exposure, we observed necrotic cells with round red nuclei but also pyknotic cells that exhibited bright blue nuclei (Figure 3A). Ranitidine significantly (P<0.05) reduced pyknosis in cells exposed to OGD (Figure 3B), whereas it had no effect on chromatin condensation in sham control cultures (data not shown). Ranitidine also reduced the number of necrotic PI-positive cells (Figure 3B).
Effect of Ranitidine on OGD-Induced Caspase 3 Activation

Apoptotic cell death in cerebral ischemia has been associated with caspase 3 activation. Accordingly, we decided to study the effect of ranitidine on OGD-induced caspase 3 activation. Six hours after OGD, there is a substantial activation of caspase 3 in neurons visualized with a specific antibody against the cleaved enzyme (Figure 4A, green label). A clearly disorganized MAP-2 labeled network (in red) is also noticeable. Preincubation with ranitidine before OGD diminished caspase 3 cleavage and prevented alteration of MAP-2 staining (Figure 4). Western blot analysis of cell extracts collected 6 hours after OGD (Figure 4B) demonstrates that MAP-2 degradation, which results from OGD (lane 2), was effectively prevented by pretreatment with ranitidine (lane 4). A reduction of caspase 3 cleavage in cell extracts from ranitidine-treated OGD cultures is clearly evident compared with untreated OGD cells (Figure 4B).

Effect of Ranitidine Treatment After OGD

To examine whether ranitidine exerts a neuroprotective action after induction of OGD, cultures were treated with ranitidine 3 or 6 hours after OGD. Twenty-four hours later, cell viability was assessed by MTT reduction assay, and parallel cultures were stained with PI and Hoechst 33258 to quantify the necrotic and apoptotic nuclei. Ranitidine significantly decreased OGD-induced cell death (Figure 5A). A significant reduction of apoptotic (67%) and necrotic (65%) cells versus untreated OGD-exposed cultures was also observed (Figure 5B).

Discussion

It is well established that during brain ischemia, a release of glutamate and cytokines takes place. HA is also suggested to be released during ischemia. We have found an increase in HA release in cortical cultures deprived of oxygen and glucose. We have also detected the presence of L-histidine decarboxylase, the enzyme responsible for HA synthesis in brain. Because no histaminergic neurons are present in the cerebral cortex, it is likely that glial cells present in our cultures are the source of released HA. Because in vitro studies have shown that HA potentiates glutamate-mediated excitotoxicity, it is tempting to suggest that inhibition of HA action during ischemia could exert a beneficial effect. In this respect, and supporting the neuroprotective effect of blocking HA action, we observed that several HA H2-receptor antagonists decreased OGD-mediated cell death, as measured by MTT reduction.

Although ischemic neuronal death was traditionally described as necrosis, in recent years evidence of ischemic-
induced apoptosis is arising.1 Thus, it is now believed that a
good neuroprotective therapy for cerebral ischemia should be
able to reduce apoptotic death.18 By monitoring the effect of
H2-receptor antagonists on the necrotic and apoptotic compo-
nent of OGD-mediated cell death, we have observed that
ranitidine reduced OGD-mediated necrosis and apoptosis.
The antiapoptotic effect of ranitidine was confirmed by a
decrease in OGD-mediated activation of caspase 3 and
MAP-2 degradation.19,20 The neuroprotective effect of raniti-
dine could then be able to antagonize HA interaction
with NMDA receptors. However, no experimental data sup-
porting this possibility has been described. Alternatively,
runitidine could act through its classical direct blockade of
HA H2-receptor stimulation. Also, we could not rule out the
possibility that the effect of ranitidine is mediated by inhibi-
tion of constitutively active H2-receptors. Up until now, there
is no clear evidence about how HA receptors stimulation
could promote cell death in the central nervous system.
However, some reports have described an HA-mediated
potentiation of NMDA receptors through H2-receptor stimu-
lation and subsequent activation of potassium channels.21

In summary, our present findings provide evidence that
ranitidine, a commonly used antigastric ulcer drug, exerts
neuroprotective actions on ischemic neural cell death even 6
hours after insult. All data together indicate that the HA
H2-receptor blockers may be very interesting compounds to
study novel and efficient treatments for cerebral ischemia.

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