White Matter Injury in Spinal Cord Ischemia
Protection by AMPA/Kainate Glutamate Receptor Antagonism

Georgios K. Kanellopoulos, MD; Xiao Ming Xu, MD, PhD; Chung Y. Hsu, MD, PhD; Xiaobin Lu, MD; Thoralf M. Sundt, MD; Nicholas T. Kouchoukos, MD

Background and Purpose—Spinal cord ischemia is a serious complication of surgery of the aorta. NMDA receptor activation secondary to ischemia-induced release of glutamate is a major mechanism of neuronal death in gray matter. White matter injury after ischemia results in long-tract dysfunction and disability. The AMPA/kainate receptor mechanism has recently been implicated in white matter injury.

Methods—We studied the effects of AMPA/kainate receptor blockade on ischemic white matter injury in a rat model of spinal cord ischemia.

Results—Intrathecal administration of an AMPA/kainate antagonist, 6-nitro-7-sulfamoyl-(f)-quinoxaline-2,3-dione (NBQX), 1 hour before ischemia reduced locomotor deficit, based on the Basso-Beattie-Bresnahan scale (0=total paralysis; 21=normal) (sham: 21±0, n=3; saline: 3.7±4.5, n=7; NBQX: 12.7±7.0, n=7, P<0.05) 6 weeks after ischemia. Gray matter damage and neuronal loss in the ventral horn were evident after ischemia, but no difference was noted between the saline and NBQX groups. The extent of white matter injury was quantitatively assessed, based on axonal counts, and was significantly less in the NBQX as compared with the saline group in the ventral (sham: 1063±44/200×200 μm, n=3; saline: 556±104, n=7; NBQX: 883±103, n=7), ventrolateral (sham: 1060±135, n=3; saline: 411±66, n=7; NBQX: 676±122, n=7), and corticospinal tract (sham: 3391±219, n=3; saline: 318±23, n=7; NBQX: 588±103, n=7) in the white matter on day 42.

Conclusions—Results indicate severe white matter injury in the spinal cord after transient ischemia. NBQX, an AMPA/kainate receptor antagonist, reduced ischemia-induced white matter injury and improved locomotor function.

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Key Words: aorta ▪ axons ▪ excitotoxins ▪ myelin ▪ paraplegia ▪ spinal cord ▪ rats

Ischemic injury to the spinal cord leading to paraplegia continues to represent a serious complication of surgery on the descending thoracic and thoracoabdominal aorta.1 Numerous surgical techniques have been proposed and are being used to attenuate the severity of the ischemic insult to the spinal cord during these extensive surgical procedures. No techniques have been found to reliably prevent intraoperative spinal cord injury. A different approach to prevent ischemic injury of the spinal cord is pharmacological prophylaxis directed at enhancing tolerance of the spinal cord to ischemia.

Glutamate is the major excitatory neurotransmitter in the central nervous system of vertebrates. Under normal conditions, neurons are exposed to physiological concentrations of glutamate in the course of excitatory neurotransmission. Such exposure is not injurious. During ischemia, a massive release of glutamate into the extracellular space,2,3 coupled with a decreased capacity of metabolically impaired glia to transport glutamate, augments injury and facilitates neuronal death.4

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Disability after spinal cord injury (SCI) is primarily caused by axonal injuries or dysfunction in the white matter. Neurological deficit, to a large extent, is determined by the lesion size in the white matter.5–7 A gray matter lesion in the cord sparing most white matter (eg, central cord syndrome) results in segmental motor or sensory dysfunction and usually does not cause deficit below the affected level. The most severe disability after SCI generally stems from loss of communication between the brain and spinal cord secondary to dysfunction of the axons that constitute the long tracts in the white matter. White matter injury in the spinal cord, even segmental, may disrupt axonal conduction in long tracts leading to paralysis below the lesion.

Studies of central nervous system ischemia have mainly focused on gray matter injury. Degeneration of the white matter after spinal cord ischemia has not been systematically
explored. The conventional view that the white matter is less vulnerable to ischemic injury as compared with the gray matter is now being questioned. Increasing in vivo evidence indicates that ischemia may primarily damage white matter in the spinal cord and the brain.\(^{9,10}\) Whereas excitotoxins play a major role in the pathogenesis of ischemic gray matter injury,\(^4\) the role of glutamate receptor action in ischemic white matter lesion is less clear. Glial elements and axons have traditionally been considered resistant to injury caused by excitotoxins exposure.\(^11\) However, activation of the AMPA/kainate glutamate receptor has recently been shown to cause oligodendrocyte death in vitro and in vivo.\(^{12,13}\) In addition, the AMPA/kainate receptor was found to mediate oligodendrocyte death after oxygen-glucose deprivation in vitro.\(^12\) Interestingly, AMPA/kainate receptor antagonism has also been found effective in salvaging white matter after traumatic SCI in the rat.\(^14\)

The present study aimed to investigate (a) the pathological effects of spinal cord ischemia induced by aortic occlusion on the white matter and (b) the efficacy of 6-nitro-7-sulfamoyl-(f)-quinoxaline-2,3-dione (NBQX), a competitive and highly potent antagonist of the AMPA/kainate glutamate receptor, in reducing the white matter injury and neurological deficit after spinal cord ischemia.

**Materials and Methods**

**Surgery**

Forty-eight Long-Evans outbred male rats (body weight 360±30 g) (Harlan Sprague-Dawley, Inc) were used in the study. All animals were allowed free access to laboratory chow and tap water in day-night regulated quarters at 24°C. Animal care complied with the “Principles of Laboratory Animal Care” and the “Guide for the Care and Use of Laboratory Animals” (NIH Publication No. 85-23, 1985) and was approved by the Animal Studies Committee, Washington University School of Medicine. The model of spinal cord ischemia used in this study has been described in detail previously.\(^{15}\) In brief, the surgery was performed under inhalation anesthesia with halothane. The tail artery and the left internal carotid artery were cannulated for monitoring the distal aortic blood pressure and the distal left internal carotid artery back pressure, respectively. The core temperature was continuously monitored with a flexible temperature probe inserted 3 cm into the rectum. During the surgical preparation, the temperature was maintained at 37.0±0.5°C with the use of a heating lamp connected to a temperature monitor and a thermostat. Heparin (100 U/kg) was administered intra-arterially before aortic occlusion. Arterial blood gases and blood glucose were determined just before aortic occlusion. A 2F Fogarty catheter was inserted through the left common carotid artery and subsequently advanced to the thoracic aorta. Inflation of the catheter balloon with 0.10 mL of 375 to 600 mg solution consistently resulted in the distribution of the dye in the subarachnoid space from the caudal cord to thoracic segments 30 minutes to 3 hours after injection. The treatment group (n=5) received 425 μg NBQX solution (Tokris Cookson) diluted in 20 μL 0.9% NaCl in a similar manner as in the saline group. We administered NBQX through the intrathecal route to avoid the nephrotoxic effects of the drug at higher doses that are required in systemic administration. The therapeutic strategies for reducing ischemic injury are directed at a specific patient population undergoing invasive surgery. Intrathecal administration of a neuroprotective agent may not pose much technical difficulty in this group of patients. The NBQX dose chosen for the present study was based on a series of preliminary experiments in which NBQX in doses ranging from 375 to 600 μg was intrathecally administered under halothane anesthesia in another set of animals (n=6). Animals that received up to 425 μg NBQX did not exhibit sedation or respiratory disturbance, and none of these animals died. However, these animals exhibited severe but transient flaccid paraplegia lasting for ~2 hours after NBQX delivery. This was followed by gradual and complete recovery of the motor function in the lower limbs within 6 hours after injection. The sham-operated group (n=7) received intrathecal injection of 20 μL 0.9% NaCl and underwent Fogarty catheter insertion in the aorta without the aortic cord with aortic occlusion. The animals were killed at either 48 hours (acute series: 8 in the saline group, 8 in the NBQX group, and 4 in the sham group) or 42 days (chronic series: 7 in the saline group, 7 in the NBQX group, and 3 in the sham group). Crede’s maneuver was used for evacuation of the urinary bladder when necessary.

**Evaluation of Hindlimb Function**

The hindlimb function was scored by means of the Basso, Beattie, and Bresnahan (BBB) open-field locomotion scale developed for traumatic SCI.\(^{17,18}\) The BBB scale ranges from 0 (no detectable movement in the hind limbs) to 21 (normal locomotion). BBB scores were recorded at 1, 6, 12, 24, and 48 hours in the acute series and on days 2, 7, 14, 21, 28, 35, and 42 in the chronic series by experienced investigators who did not conduct the surgery and were blinded to the treatment codes.

**Light Microscopy**

In both the acute and chronic series, the animals were anesthetized with an overdose of pentobarbital (150 mg/kg IP) and transcardially perfused with 0.9% NaCl for 1 minute followed by 400 mL 10% buffered formalin. The cadavers were kept at 4°C for 4 hours. The spinal cord was harvested and postfixed in the same fixative at 4°C overnight. The 3rd and 4th lumbar spinal cord segments were isolated and embedded in paraffin. Consecutive 8-μm sections were cut serially and were mounted and stained with hematoxylin and eosin and Nissl. In the acute series, spinal cord damage was assessed by means of a semiquantitative scoring system in a blinded fashion as previously described.\(^{19}\) A score was given according to the extent and severity of histopathological changes in 3 sets of hematoxylin and eosin–stained and Nissl-stained specimens in the mid-segment of the 4th lumbar cord. The grading of the acute gray matter injury was based on percent abnormal or dead neurons in the ventral horns: 0, no neuronal injury or death; 1, mild damage (<10%); 2, moderate damage (10% to 50%); and 3, severe damage (>50%). Three regions of the spinal cord gray matter were scored: the ventral horn with the large motoneurons (Rexed’s laminae 8 and 9), the intermediate gray matter (laminae 7 and 10), and the dorsal horn (laminae 1 to 6).
Physiological Parameters in Control and NBQX Groups

<table>
<thead>
<tr>
<th>Group</th>
<th>$P_{a}O_{2}$, mm Hg</th>
<th>$P_{a}CO_{2}$, mm Hg</th>
<th>pH</th>
<th>Glucose, mg/dL</th>
<th>MABP, mm Hg</th>
<th>DABP, mm Hg</th>
<th>BDr, mL</th>
<th>Rectal Temperature Before, °C</th>
<th>Rectal Temperature After, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>226±40</td>
<td>39±8</td>
<td>7.37±0.06</td>
<td>103±20</td>
<td>91±12</td>
<td>7.6±1.8</td>
<td>10±2</td>
<td>36.9±0.18</td>
<td>34.2±0.7</td>
</tr>
<tr>
<td>NBQX</td>
<td>229±44</td>
<td>36±4</td>
<td>7.36±0.04</td>
<td>111±13</td>
<td>84±13</td>
<td>7.5±0.8</td>
<td>10±4</td>
<td>36.9±0.18</td>
<td>34.3±0.9</td>
</tr>
</tbody>
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MABP indicates mean arterial blood pressure before aortic occlusion; DABP, maximal distal aortic blood pressure during aortic occlusion; and BDr, volumes of blood drained during aortic occlusion.

Values are expressed as mean±SD.

Rectal temperature was recorded just before aortic occlusion and at 3 hours after reperfusion.
Histopathology in the Acute Series

On day 2, there were no evident histopathological changes in the 4th lumbar spinal cord segment in the sham group. In contrast, significant ischemic injury was noted in the saline group. In the gray matter, many neurons showed features characteristic of ischemic cell death, including cytoplasmic eosinophilia with disintegration of cytoarchitecture and nuclear pyknosis. Shrinkage of cell bodies with occasional budding were noted in some of these ischemic neurons. In addition, vacuolation was noted in the neuropil. In the white matter, vacuolation was widespread and was prominent in the ventral and ventrolateral funiculi (Figure 3). The dorsolateral funiculus was also affected (see below). These histopathological abnormalities were similar to those described in this model previously. Animals in the NBQX group showed similar histopathological changes. There was no difference in the degree of histopathological damage in the spinal cord gray matter between the saline and the NBQX groups on day 2 (Figure 4). However, the grading of the acute white matter damage in the ventral and ventrolateral white matter of animals treated with NBQX (0.8 ± 0.5, n = 8) was significantly less than the saline group (2 ± 0.49, n = 8 *P < 0.05) (Figure 4).

Axonal and Neuronal Counts in the Chronic Series

In sham-operated animals, axons with variable diameters were clearly defined by SMI-31 immunoreactivity, as shown in the selected areas of the ventral and ventrolateral white matter (Figure 5, A and B) and the corticospinal tract (data not shown) at the 4th lumbar spinal cord segment on day 42. In the ventral white matter, the density of labeled axons in the sham group (1063 ± 44/200 × 200 μm, n = 3) was substantially greater than those in the ischemic animals treated with saline (559 ± 104/200 × 200 μm, n = 7) or NBQX (883 ± 103/200 × 200 μm, n = 7). The difference in axonal density was also significant between the saline and NBQX groups (*P < 0.05). Similar findings were noted in the ventrolateral white matter (sham: 1060 ± 135/200 × 200 μm; saline: 12.7 ± 7.0, n = 7, *P < 0.05).
Eleven minutes of ischemia resulted in a loss of 47%, 58%, and 91% of SMI-31–labeled axons, respectively, in the ventral and ventrolateral white matter areas and the corticospinal tract of the 4th lumbar spinal cord segment at 6 weeks after the insult. We performed axonal counts in the lumbar region because spinal cord damage in this model is mostly seen distal to the lower thoracic spinal cord. We evaluated the numbers of axons at 6 weeks after transient ischemia, avoiding intermediate morphological changes that might compound quantitative axonal counts. It is unclear whether ischemia may induce changes in the structure of axonal neurofilaments, resulting in the loss of phosphorylated epitopes and therefore reduced SMI-31–labeled axonal counts in the postischemic white matter. Descriptions of morphological changes in the white matter of the rat spinal cord 1 to 2 months after transient ischemia have been previously reported. In one of these studies, degenerating axons containing aggregates of microtubules and dense bodies, disintegrating myelin sheaths, and scavenger cells were seen in the corticospinal tract of the lumbar cord 32 days after injury. The postischemic loss of axons in the white matter of the 4th lumbar spinal cord segment may have resulted from local axonal injury or from a lesion in the more proximal axonal segments up to their cell bodies. The latter process, called anterograde or Wallerian degeneration, has been known for decades. The relative contribution of local injury and anterograde degeneration in the observed reduction of SMI-31–labeled axons in the lumbar cord white matter after ischemia is unclear. The pronounced loss of labeled axons in the corticospinal tract after ischemia may be related to the previously demonstrated higher blood flow to the corticospinal tract compared with other white matter regions in the normal rat spinal cord. Higher blood flow may imply a higher degree of metabolic activity under physiological conditions and a greater vulnerability to ischemic injury. In addition to the loss of labeled axons at 6 weeks after injury, significant morphological changes, such as prominent vacuolation of varying diameters, were observed in the white matter at 48 hours. Similar changes have been previously reported in the same model. The ultrastructural changes reported in the same model.

Discussion

In this study, impairment of locomotor function was evident after ischemia, consistent with extensive axonal degeneration, based on quantitative analysis. NBQX pretreatment improved locomotor function and attenuated axonal loss up to 6 weeks after ischemia. However, the gray matter damage was not affected by NBQX pretreatment.

White Matter Damage After Spinal Cord Ischemia

Eleven minutes of ischemia resulted in a loss of 47%, 58%, and 91% of SMI-31–labeled axons, respectively, in the ventral and ventrolateral white matter areas and the corticospinal tract of the 4th lumbar spinal cord segment. Significant difference between *sham and vehicle control (ischemia with saline treatment) groups and between **vehicle control and NBQX (ischemia with NBQX treatment) groups.
that underlie vacuolation in the spinal cord white matter early after ischemia is not known. However, segmental swelling of axons and astrocyte processes as well as formation of spaces between myelin sheaths and axolemma were responsible for the production of vacuoles in the brain white matter 12 to 24 hours after permanent ligation of the middle cerebral artery in rats.9

**NBQX and White Matter Damage After Spinal Cord Ischemia**

In the present study, pretreatment with NBQX reduced the loss of SMI-31–labeled axons in the ventral white matter from 47% to 17% in the saline group and in the ventrolateral area from 61% to 36% in the saline group. Similarly, NBQX administration reduced the loss of labeled axons in the corticospinal tract from 91% to 83% in control. The effect of NBQX on ischemic axonal loss in the white matter has not been previously reported. Although there are important differences in the pathophysiology between spinal cord ischemia and trauma, it is interesting to note that NBQX significantly increased the serotonin immunoreactivity caudal to the injury site 4 weeks after injury in a rat model of spinal cord compression trauma.14 This observation suggests that the AMPA/kainate receptor mediates the damage of descending axonal pathways caused by mechanical injury and that NBQX is effective in attenuating damage to these long tracts. In addition to the preservation of white matter axons, NBQX administration decreased the severity of histopathological changes in the ventral and ventrolateral funiculi of the white matter 2 days after the onset of reperfusion. This finding is in accord with findings from a rabbit model of SCI induced by combining ischemia with administration of exogenous glutamate, in which NBQX appeared to reduce the white matter damage at 48 hours after insult.26

**AMPA/Kainate Glutamate Receptor and Pathogenesis of Axonal Degeneration After Spinal Cord Ischemia**

Our findings support the contention that AMPA/kainate receptor activation contributes to axonal loss and white matter damage after ischemia and reperfusion. It has been demonstrated from studies with the in vitro rat optic nerve that anoxia may directly injure axons by disrupting ion homeostasis,7,22 leading to gradual Ca$^{2+}$ accumulation in axons and activation of deleterious cascades. There is no evidence indicating that neuronal excitatory amino acid receptors could modulate ischemia-induced ionic disturbances in axons. It therefore appears unlikely that NBQX preserved axons in this study by attenuating direct ischemic injury to axons. This view is further supported by the time-honored observation that exposure of neurons to excitotoxins produces morphological changes that spare the axons.4 Loss of myelinated axons in the white matter may also be secondary to injury or death of oligodendrocytes, which myelinate axons in the central nervous system. There is increasing evidence that oligodendrocytes may be highly vulnerable to ischemic injury. In a rat model of permanent middle cerebral artery occlusion, pathological changes in oligodendrocytes appeared early after the onset of ischemia and appeared to be concomitant with but independent of neuronal perikaryal injury.9 In a different rat model of sustained moderate brain ischemia, the earliest and perhaps primary change in the white matter was disturbed metabolism and synthesis of myelin.29 Furthermore, there is accumulating evidence that the marked elevations in extracellular glutamate concentration, which accompany ischemic injury of the brain2 and the spinal cord,3,30 might mediate the oligodendrocyte ischemic injury. In the case of white matter, nonsynaptic mechanisms for extracellular release of excitatory neurotransmitters are important. It has been suggested that glutamate could leak out of axons during ischemia through the Na$^{+}$–K$^{+}$-glutamate transporter, creating high neurotransmitter concentrations in the restricted submyelinic and interlamellar spaces.28 Ischemia-reperfusion injury also may cause glutamate efflux from energy-depleted astrocytes31 through multiple mechanisms, including reversed glutamate transport22 and swelling-evoked33 or Ca$^{2+}$-dependent34,35 release. Glutamate also might spill into the white matter from the neighboring ischemic gray matter.31 Ischemia-induced increases in extracellular glutamate concentration could result in toxic activation of functional AMPA/kainate glutamate receptors on oligodendrocytes and astrocytes.11–13,36 Differentiated rat oligodendrocytes have been recently found to be highly vulnerable to AMPA/kainate receptor–mediated excitotoxic death in vitro, whether induced by exposure to agonists12,13 or by deprivation of oxygen and glucose.12 Injection of AMPA/kainate receptor agonists into the rat thalamus59 or external capsule13 caused marked oligodendrocyte death. In the present study, ischemic destruction of axons in the spinal cord might result from soluble mediators, such as oxidative products or free radicals, produced by glial cells after toxic exposure to glutamate. In addition, axons might degenerate after ischemia-induced excitotoxic death of the oligodendrocytes. Myelin-forming glial cells are capable of modifying axonal morphology and axonal transport.37,38 Findings from a recent study in vivo indicate that degeneration of axons in the central nervous system may occur when crucial local support from oligodendrocytes becomes inadequate.39 Antagonism of AMPA/kainate receptors on glial cells11 may have preserved white matter axons in the present study by attenuating ischemia-induced excitotoxic injury or death of oligodendrocytes.

**NBQX and Gray Matter Degeneration After Spinal Cord Ischemia**

NMDA receptor blockade has been shown to improve spinal cord tolerance to ischemia.40 In view of the prominent role of NMDA receptor mechanism in gray matter injury, the neuroprotective effects of NMDA antagonists, such as MK-801,41 CGS-19755, and LY233053,42 in spinal cord ischemia might be on gray matter. In the present study, pretreatment with NBQX failed to attenuate the severity of histopathological changes in the lumbar cord gray matter 2 days after ischemia in this model. Furthermore, administration of NBQX was not associated with preservation of neurons in the ventral horns of the lumbar cord 42 days after ischemia, suggesting that NBQX is not effective against neuronal degeneration in the posts ischemic gray matter. In a previous
NBQX and Locomotor Function After Spinal Cord Ischemia

In the present study, intrathecal administration of NBQX before ischemia resulted in significant improvement of the locomotor function as compared with vehicle-treated controls. The improved locomotor outcome was apparent by 24 hours after the insult and was maintained throughout the 6-week follow-up period. Our findings are in agreement with observations in previous studies showing functional improvement after NBQX treatment in rat and rabbit. In addition, administration of a different AMPA antagonist, LY293558, given 5 minutes after the onset of reperfusion, significantly increased the duration of ischemia required to produce paraplegia in an acute rabbit model of spinal cord ischemia.

The spinal cord was not examined specifically for white matter histopathology in that study. In both the acute and the chronic phases of the present study, the improved locomotor function in animals pretreated with NBQX was associated with decreased severity of degeneration in the white but not in the gray matter of the lumbar spinal cord.

Timing of NBQX Treatment

Blockade of glutamate receptors to reduce ischemia-induced spinal cord damage may have a very limited therapeutic window. In the present study, NBQX was tested in a pretreatment regimen. The effectiveness of NBQX in a posttreatment dosing was not examined. Because the present study aimed to explore preventive measures that may protect spinal cord from ischemic insult sustained in elective surgery of the aorta, an effective pretreatment regimen is clinically relevant. Under the circumstances, pretreatment to prevent the injury is preferred to posttreatment.

Concluding Remarks

Spinal cord ischemia with resultant neurological deficit continues to be a serious complication after surgery on the descending thoracic and thoracoabdominal aorta of patients. Our data support the notion that white matter degeneration is an important mechanism of ischemia-induced paralysis. NBQX treatment attenuated the postischemic white matter degeneration, possibly by favorably interfering with axono-glial interactions and improved locomotor function. Administration of agents that modify the function of AMPA/kainate glutamate receptors before surgery may be an efficacious measure in attempts to prevent white matter degeneration caused by perioperative spinal cord ischemia.

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References

The neuroprotection of NBQX, an AMPA/kainate glutamate receptor antagonist, in cerebral ischemia was first reported in 1990. This generated tremendous interest and offered hope that cerebral ischemia could be ameliorated by the AMPA receptor antagonist. Enthusiasm for the therapeutic potential was significantly dampened later by the fact that NBQX is toxic to the liver. Nevertheless, several second-generation AMPA receptor antagonists have been developed. These drugs primarily target the ischemic neurons. Recent studies have demonstrated that inhibition of the AMPA/kainate receptor can provide neuroprotection against excitotoxicity in white matter oligodendrocytes and a reduction in functional impairment after spinal cord trauma.

In this well-written and carefully performed study, Kanellopoulos and colleagues have furthered the preclinical utility of NBQX by showing amelioration of white matter injury in a rat model of spinal cord ischemia. In view of the failure of current neuroprotective agents that mainly target neurons and endothelial cells, this study provides further consideration for alternative therapeutic approaches that target white matter injury in ischemic stroke.

References


Editorial Comment

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