Edaravone Prevents Retinal Degeneration in Adult Mice Following Optic Nerve Injury

Goichi Akiyama, Yuriko Azuchi, Xiaoli Guo, Takahiko Noro, Atsuko Kimura, Chikako Harada, Kazuhiko Namekata, and Takayuki Harada

Visual Research Project, Tokyo Metropolitan Institute of Medical Science, Tokyo, Japan

METHODS. Two microliters of edaravone (7.2 mM) or vehicle were injected intraocularly 3 minutes after ONI. Optical coherence tomography, retrograde labeling of retinal ganglion cells (RGCs), histopathology, and immunohistochemical analyses of phosphorylated apoptosis signal-regulating kinase-1 (ASK1) and p38 mitogen-activated protein kinase (MAPK) in the retina were performed after ONI. Reactive oxygen species (ROS) levels were assessed with a CellROX Green Reagent.

RESULTS. Edaravone ameliorated ONI-induced ROS production, RGC death, and inner retinal degeneration. Also, activation of the ASK1-p38 MAPK pathway that induces RGC death following ONI was suppressed with edaravone treatment.

CONCLUSIONS. The results of this study suggest that intraocular administration of edaravone may be a useful treatment for posttraumatic complications.

Keywords: edaravone, oxidative stress, neuroprotection, ASK1, retinal ganglion cell

Edaravone is a free radical scavenger that has been used clinically to treat acute brain infarction and amyotrophic lateral sclerosis (ALS). Edaravone quenches hydroxyl radicals (OH) and inhibits lipid peroxidation dependent and independent of OH. Edaravone ameliorated ONI-induced ROS production, RGC death, and inner retinal degeneration. Also, activation of the ASK1-p38 MAPK pathway that induces RGC death following ONI was suppressed with edaravone treatment.

Edaravone is a free radical scavenger that has been used clinically to treat acute brain infarction and amyotrophic lateral sclerosis (ALS). Edaravone quenches hydroxyl radicals (OH) and inhibits lipid peroxidation dependent and independent of OH.12,13 In an in vitro cell culture study using the RGC-5 to study the neurobiology of RGCs, edaravone scavenged the intracellular OH, superoxide anion (O2−), and hydrogen peroxide (H2O2) while demonstrating the strongest scavenging activity against OH.14 Recent studies have shown that oxidative stress plays an important role in many ocular diseases including glaucoma.15–18 Interestingly, edaravone attenuates retinal ischemia/reperfusion injury in rats19 and retinal damage in experimental rats with glaucoma showing high intraocular pressure.20 These findings suggest a possibility that edaravone protects RGCs by scavenging reactive oxygen species (ROS). In the present study, we examined the effects of intraocular injection of edaravone on RGC protection following ONI.

MATERIALS AND METHODS

Mice and ONI

Experiments were performed using 8- to 10-week-old C57BL/6j mice (CLEA Japan, Tokyo, Japan) in accordance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research. Mice were anesthetized with sodium pentobarbital before ONI. Optic nerves were exposed intraorbitally and crushed at approximately 0.5 to 1.0 mm from the posterior pole of the eyeball with fine surgical forceps for 5 seconds.21,22 Two microliters of edaravone (7.2 mM; Mitsubishi Tanabe Pharma Co., Osaka, Japan) or vehicle (phosphate-buffered saline [PBS]) were injected intraocularly to control mice or 3 minutes after ONI. The mice were euthanized at 7 days after the injection. Once the surgery was completed, the mice were assigned identification numbers randomly so that the nature of treatment (vehicle or edaravone) was masked to evaluators of the results.

Imaging Acquisition of Spectral-Domain Optical Coherence Tomography (SD-OCT)

SD-OCT (RS-5000; Nidek, Aichi, Japan) examinations were performed at just before and 7 days after ONI as previously...
Edaravone Ameliorates Optic Nerve Injury

RESULTS

Edaravone Protects Retinal Neurons After ONI

To investigate whether edaravone prevents retinal degeneration, we administered edaravone or PBS intraocularly to adult mice 3 minutes after ONI (Fig. 1A). We visualized retinal layers in living mice using SD-OCT, a noninvasive imaging technique that can be used to acquire cross-sectional tomographic images of the retina in vivo.22-24 The average thickness of the GCC, which includes the nerve fiber layer, GCL, and the inner plexiform layer, was markedly greater in edaravone-treated mice compared with PBS-treated mice (Fig. 1B). For quantitative analysis, GCC was measured by scanning the retina in a circle centered around the optic nerve disk (Fig. 1C), and the average GCC thickness was determined from acquired images (Fig. 1D). GCC thickness was significantly reduced in PBS-treated mice (73.8 ± 0.5 μm, n = 6; P < 0.01) compared with control mice (82.2 ± 0.9 μm, n = 6), but edaravone signiﬁcantly suppressed the thinning of the GCC (81.3 ± 1.3 μm, n = 6; P = 0.92) (Fig. 1E). In addition, edaravone showed no toxic effects in control mice (82.6 ± 0.7 μm, n = 6; P = 0.99) (Figs. 1B, 1E).

We also analyzed the histopathology of the retina before and after ONI (Fig. 2A). ONI induced severe RGC loss in PBS-treated mice (290 ± 77 cells/section, n = 6; P < 0.01) compared with control mice (563 ± 31 cells/section, n = 6), but the number of surviving neurons in the GCL was significantly higher in edaravone-treated mice (445 ± 64 cells/section, n = 6; P < 0.05) (Figs. 2A, 2B). Also, the thickness of the IRL was signiﬁcantly greater in edaravone-treated mice (111 ± 6 μm, n = 6; P < 0.05) compared with PBS-treated mice (92 ± 2 μm, n = 6) (Figs. 2A, 2C), which are consistent with the results from the OCT (Fig. 1E). Edaravone showed no toxic effects in control mice (555 ± 20 cells/section, n = 6; P = 0.99 and 121 ± 4 μm, n = 6; P = 0.58) (Fig. 2). These data indicate that edaravone treatment prevents retinal degeneration following ONI.

Because the GCL contains cell types other than RGCs including displaced amacrine cells,29 we next performed retrograde labeling of RGCs with FG and determined the effect of edaravone on RGC survival. Consistent with the results of cell counting in the GCL (Fig. 2B), the RGC number...
in edaravone-treated mice (2168 ± 687 cells/mm², n = 6; P < 0.01) was significantly increased compared with PBS-treated mice (1466 ± 49 cells/mm², n = 6) in the central retina (Fig. 3). In addition, the RGC number in edaravone-treated mice (1782 ± 62 cells/mm², n = 6; P < 0.01) was significantly increased compared with PBS-treated mice (1118 ± 48 cells/mm², n = 6) in the peripheral retina (Fig. 3B). These data demonstrate that edaravone prevents RGC death all across the retina following ONI.

**Effects of Edaravone on ONI-Induced RGC Death Signaling**

We previously reported that activation of the ASK1-p38 mitogen-activated protein kinase (MAPK) pathway was detected at 3, 4, and 6 hours after ONI and involved in ONI-induced RGC death.²²,³⁰ We, therefore, examined the effect of edaravone on ONI-induced activation of the ASK1-p38 MAPK signaling at 6 hours after ONI. Immunohistochemical analysis revealed that ONI induces expression of phosphorylated (activated) ASK1 (1.86 ± 0.13-fold, n = 6; P < 0.05) and p38 MAPK (2.34 ± 0.17-fold, n = 6; P < 0.05) primarily in the GCL (Fig. 4). Intravitreal injection of edaravone significantly suppressed the expression levels of both phosphorylated ASK1 (1.20 ± 0.07-fold, n = 6; P < 0.05) and p38 MAPK (1.43 ± 0.26-fold, n = 6; P < 0.05) (Fig. 4). These results suggest that edaravone prevents RGC degeneration by suppressing the activation of the ASK1-p38 MAPK pathway.

**Edaravone Suppresses ROS Production Following ONI**

Previous studies have shown that production of ROS after ONI occurs primarily in RGCs.²⁸,⁵¹ To examine the effect of edaravone on ONI-induced ROS production, we performed staining of ROS using CellROX green reagent in the whole-mount retina. Because ROS is a powerful activator of ASK1-p38 MAPK signaling, we also performed CellROX green reagent analyses at 6 hours after ONI. ONI-induced ROS production in the PBS-treated retinas (3.25 ± 0.37-fold, n = 6; P < 0.05) compared with the control retinas (1.00 ± 0.28-
FIGURE 2. Effects of edaravone on retinal degeneration following ONI. (A) Retinal sections stained with hematoxylin and eosin in control and edaravone-treated mice. Scale bar: 50 μm. (B, C) Quantification of the cell number in the GCL (B) and IRL thickness (C) in PBS- and edaravone-treated mice. The data are presented as mean ± SEM of six retinas for each experiment. *P < 0.05, **P < 0.01. INL, inner nuclear layer; ONL, outer nuclear layer.

FIGURE 3. Effects of edaravone on RGC death following ONI. (A) Representative images of retrograde-labeled RGCs in the central retina. Scale bar: 50 μm. (B) Quantitative analyses of RGCs in the central and peripheral areas of the retina. The data are presented as mean ± SEM of six retinas for each experiment. *P < 0.05.
fold, \( n = 6 \), but edaravone clearly suppressed the ROS production (1.66 ± 0.39-fold, \( n = 6; P < 0.05 \)) (Fig. 5). These results suggest that edaravone prevents RGC death by suppressing cell death pathways through the inhibition of ROS production after ONI.

**DISCUSSION**

In this study, we reported that intraocular injection of edaravone exerts neuroprotective effects in an ONI model. Sequential in vivo retinal imaging revealed that post-ONI...
treatment with edaravone was effective for maintaining the retinal structure. We also demonstrated that edaravone suppressed the production of ROS and stress-induced ASK1-p38 MAPK signaling, which leads to RGC survival following ONI. The ASK1-p38 MAPK pathway is activated in response to multiple types of stress and implicated in diseases such as cancer, Alzheimer’s disease, and multiple sclerosis. This signaling pathway also plays a role in RGC death and optic nerve degeneration under various conditions. Post-ONI of human glaucoma. Therefore, drugs with antioxidant properties, including edaravone, are good candidates for the treatment of glaucoma and optic neuropathy. Intraocular injection of edaravone plus oral spermidine and 3-methyl-1-phenyl-2-pyrazolin-5-one may have synergistic effects on RGC protection.

Recent studies have indicated that development of new uses for existing drugs can be extremely beneficial to the healthcare industry. Consequently, drug repurposing is emerging across various fields, including the central nervous system. We recently reported that valproic acid (VPA) protects RGCs from glutamate neurotoxicity in a mouse model of normal tension glaucoma. Similarly, an antioxidant, γ-lipoic acid, delivered through the diet protects RGCs in DBA/2J mice, an animal model that recapitulates the slow, progressive nature of human glaucoma. Therefore, drugs with antioxidant properties, including edaravone, are good candidates for the treatment of glaucoma and optic neuropathy. Intraocular injection of edaravone plus oral spermidine and γ-lipoic acid may have synergistic effects on RGC protection.

Oxidative stress is thought to be an important risk factor in human glaucoma. Based on our results, it is plausible that edaravone suppressed several ONI-induced RGC death signals including the ASK1-p38 MAPK pathway by suppressing oxidative stress in RGCs. We recently reported that oral treatment of spermidine, a polyamine compound found in ribosomes and living tissues, has strong antioxidant effects and suppresses RGC death in mouse models of ONI and normal tension glaucoma. Similarly, an antioxidant, γ-lipoic acid, delivered through the diet protects RGCs in DBA/2J mice, an animal model that recapitulates the slow, progressive nature of human glaucoma. Therefore, drugs with antioxidant properties, including edaravone, are good candidates for the treatment of glaucoma and optic neuropathy. Intraocular injection of edaravone plus oral spermidine and γ-lipoic acid may have synergistic effects on RGC protection.

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