Statin Inhibits Leukocyte-Endothelial Interaction and Prevents Neuronal Death Induced by Ischemia-Reperfusion Injury in the Rat Retina

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**Background:** Retinal ischemia–induced neuronal death is believed to be a direct causal process in the development of many ocular diseases. The 3-hydroxy-3-methylglutaryl coenzyme A reductase inhibitor, statin, is known to improve endothelial function in proinflammatory conditions.

**Objective:** To investigate the effects of statin on leukocyte accumulation during ischemia-reperfusion injury and on subsequent retinal damage.

**Methods:** Transient retinal ischemia was induced in Long-Evans rats for 60 minutes using temporal ligation of the optic nerve. Leukocyte-endothelial interactions in the postischemic retina were evaluated in vivo with a scanning laser ophthalmoscope. Statin was administered 5 minutes before the induction of retinal ischemia. P-selectin and intercellular adhesion molecule-1 (ICAM-1) gene expression in the postischemic retina were studied with the semi-quantitative polymerase chain reaction. Histologic studies were carried out to evaluate retinal damage.

**Results:** The preadministration of statin attenuated the rolling and accumulation of leukocytes, decreased P-selectin and ICAM-1 expression, and reduced the number of apoptotic cells in the retina. Furthermore, histologic evaluation 168 hours after reperfusion showed that statin significantly diminished the resultant retinal tissue damage. The neuroprotective effect of statin was abolished when it was administered along with a nitric oxide synthase inhibitor, nitroglycerine-nitro-L-arginine methyl ester.

**Conclusion:** Statin may exert neuroprotective effects by inhibiting leukocyte-endothelial interaction through the release of nitric oxide from the endothelium.

**Clinical Relevance:** As a result of its efficacy in preventing retinal neuronal death, statin may be developed into a novel therapeutic modality for many ocular ischemic diseases.

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**THE ISCHEMIA-REPERFUSION MODEL**

The ischemia-reperfusion model has been established and commonly used in the retinal microvasculature of rats to induce neuronal death in the retina and thereby treat many ocular diseases, including diabetic retinopathy and glaucoma. This model has demonstrated that leukocytes play a critical role in ischemia-reperfusion injury. Prevention of the recruitment of leukocytes to retinal tissue reduces ischemia-reperfusion injury by blocking the leukocyte adhesion molecules P-selectin and intercellular adhesion molecule-1 (ICAM-1). The 3-hydroxy-3-methylglutaryl coenzyme A (HMG-CoA) reductase inhibitors, collectively referred to as statins, have been broadly used as an important therapeutic modality for hypercholesterolemia. These inhibitors exert their biological effects by blocking the conversion of HMG-CoA to mevalonate. The subsequent lipid-lowering effect is correlated with decreased coronary and cerebrovascular events, improving survival rates in patients with coronary artery disease. Recent studies have also suggested that in addition to inhibiting cholesterol synthesis, statins have so-called pleiotropic effects and may contribute to the diminution of cerebrovascular and cardiovascular risks, even in patients with normocholesterolemia. Several investigators have provided evidence that statins administered to animals with normocholesterolemia protect the vascular endothelium from damage caused by inflammatory processes. Statins up-regulate and activate endothelial (type 3) nitric oxide synthase (eNOS) and decrease the expression of cell adhesion molecules in the endothelial cells.

In this context, amelioration of endothelial function through the pleiotro-
pic actions of statins could also be beneficial in glaucoma for protecting retinal neurons from death. In our study, we examined this possibility using the ischemia-reperfusion model in the rat retinal microvasculature.

METHODS

ANIMAL AND ISCHEMIA MODEL

Male pigmented Long-Evans rats (200-250 g) were used in this study. All experiments were performed in accordance with the Association for Research in Vision and Ophthalmology Statement for the Use of Animals in Ophthalmic and Vision Research.

Transient retinal ischemia was induced in the right eye of each rat according to the method of Stefansson et al, with slight modifications. Rats were anesthetized with a mixture (1:1) of xylazine hydrochloride (4 mg/kg) and ketamine hydrochloride (10 mg/kg). The pupils were dilated with 0.5% tropicamide and 2.5% phenylephrine hydrochloride. After lateral conjunctival peritomy and disinsertion of the lateral rectus muscle, the optic nerve head of the right eye was exposed using blunt dissection. A 6-0 nylon suture was passed around the optic nerve and tightened until the blood flow ceased in all of the retinal vessels. After 60 minutes of ischemia, complete nonperfusion was confirmed through an operating microscope, and the suture was removed. Reperfusion of the vessels was also observed through the operating microscope.

CHEMICALS AND DRUG ADMINISTRATION

The effects of 2 statins were evaluated at each drug’s daily clinical dose for hyperlipidemia. Pravastatin sodium and cerivastatin sodium were generously provided by Sankyo Co, Ltd (Tokyo, Japan), and Bayer Co, Ltd (Leverkusen, Germany), respectively. Nitroglycerine-nitro-L-arginine methyl ester (L-NAME) was obtained from Sigma Chemical Co (St Louis, Mo), and acridine orange was obtained from Wako Pure Chemicals (Osaka, Japan). Pravastatin (0.5 mg/kg), cerivastatin (0.1 mg/kg), or L-NAME (5 mg/kg) was given intravenously 5 minutes before the induction of ischemia. For controls, the same volume of saline was administered. To examine the short-term effects of statin, the same amount of the drug was also given intravenously 15 minutes before acridine orange digital fluorography.

ACRIDINE ORANGE DIGITAL FLUOROGRAPHY

Acridine orange digital fluorography has previously been described in detail. The evaluation of leukocyte dynamics was performed 12 hours after reperfusion in both statin- and vehicle (phosphate-buffered saline [PBS])–treated groups because previous studies had confirmed that the number of rolling leukocytes reached its peak 12 hours after ischemia-reperfusion induction. For acridine orange digital fluorography, rats were anesthetized with the same agent used before ischemia induction, and the pupils were dilated. A contact lens was placed on the cornea to maintain transparency throughout the experiments. Each rat had a catheter inserted into the tail vein and was placed on a movable platform. Body temperature was maintained between 37°C and 39°C throughout the experiment, and arterial blood pressure was monitored with a blood pressure analyzer (IITC Inc, Woodland Hills, Calif). Acridine orange (0.1% solution in saline) was injected continuously through the catheter for 1 minute at a rate of 1 ml/min.

Immediately after the acridine orange solution was infused intravenously, leukocytes were stained selectively among the circulating blood cells. The leukocytes that had accumulated in the retina remained fluorescent for approximately 2 hours. Thirty minutes after the injection, the accumulated leukocytes were identified as distinct fluorescent dots with the highest contrast. The images were recorded on a standard videotape at the rate of 30 frames per second and analyzed with an image analysis system, which consisted of a computer equipped with a video digitizer (Radius, San Jose, Calif), as described elsewhere in detail. Using this system, we determined both the flux of leukocytes rolling along the lining of major vessels and the leukocyte rolling velocity.

The number of rolling leukocytes in each major retinal vein was calculated as the number of rolling leukocytes along each vein for 1 minute at a distance of 200 µm from the optic disc center (ie, leukocyte flux). The average of the individual numbers was used as the number of rolling leukocytes for each rat. The velocity of rolling leukocytes was calculated as the time required for a leukocyte to travel a given distance (30 µm) along the vessel.

We also evaluated the number of leukocytes that had accumulated in the retinal microcirculation 30 minutes after acridine orange injection. The number of fluorescent dots in the retina within 8 to 10 areas of 100 square pixels at a distance of 1 disc diameter from the edge of the optic disc was counted and averaged. This was used as the number of accumulated leukocytes in the retinal microcirculation for each rat.

After the previously described laser ophthalmoscopic images were obtained, the rat was euthanized with an overdose of anesthesia. The eye was enucleated to determine a calibration factor to convert values measured on the computer monitor (in pixels) into absolute values (in micrometers).

SEMIQUANTIFICATION OF GENE EXPRESSION OF P-SELECTIN AND ICAM-1

Five eyes from 5 rats each in the statin-treated, vehicle-treated, and nonsurgically treated control groups were obtained to evaluate the gene expression of adhesion molecules P-selectin and ICAM-1. Twelve hours after reperfusion, the eyes were enucleated, and the retina was collected from the posterior segment. The total RNA was isolated from the retina according to the acid guanidinium thiocyanate-phenol-chloroform extraction method. The extracted RNA was quantified, and 5 µg of the RNA was reverse-transcribed into complementary DNA (cDNA) with a first strand cDNA synthesis kit (Life Technologies Inc, Gaithersburg, Md). The polymerase chain reaction (PCR) was performed with the following conditions: denaturation at 94°C for 30 seconds, annealing at 55°C for 1 minute, and polymerization at 72°C for 1 minute. The reaction was carried out for 30 cycles for P-selectin and 25 cycles for glyceraldehyde-3-phosphate dehydrogenase (GAPDH). The primers for P-selectin, ICAM-1, and GAPDH were as follows: CAAAGGAACACAGGACT (sense) and AATGGCTTCACAGGTTGCA (antisense); GACACAAAGGAGGAGAAAG (sense) and GAGAAGCGCCAAACCCGATG (antisense); and TGGCACAGTCAAGGCTGAGA (sense) and GCTAGGAGGGAAATCGTG (antisense), respectively. Nucleotide sequencing and restriction pattern analysis confirmed that PCR products were derived from the target cDNA sequences. The PCR product of ICAM-1 was semiquantitatively analyzed with NIH Image version 1.61 statistical software (National Institutes of Health, Bethesda, Md).

TUNEL STAINING

Twenty-four hours after reperfusion, the eyes were enucleated, and we performed TUNEL (terminal deoxynucleotidyl transferase–mediated deoxyuridine triphosphate nick-end la-
ing of leukocytes along the major retinal veins was observed 24 hours after reperfusion. Four eyes from 4 rats each in the statin-treated, vehicle-treated, and nonsurgically treated control groups were obtained to evaluate the staining. Rats were perfusion-fixed with 4% paraformaldehyde/PBS before enucleation. The enucleated eyes were further fixed for 2 hours at 4°C in 4% paraformaldehyde/PBS, washed for 5 minutes in PBS, gently shaken overnight at 4°C in 15% sucrose/0.1 M PBS, embedded in a tissue processor (Tissue-Tek; Miles Inc, Elkhart, Ind), and frozen in liquid nitrogen. A cryostat was used to cut 6-mm sections, which were collected onto silanized slides (DAKO Japan, Kyoto) and air dried. After being rinsed in PBS and undergoing a reaction with proteinase K, the sections were incubated at 37°C with terminal deoxuryridine triphosphate (dUTP) transferase and biotinylated dUTP in a terminal deoxynucleotidyl transferase buffer (30M Tris; pH, 7.2; 140mM sodium cacodylate; 1M cobalt chloride) for 60 minutes in a moist chamber. The sections were then processed for avidin-peroxidase activity, counterstained with propidium iodide (Sigma, St Louis, Mo), and examined using a scanning laser confocal microscope (Bio-Rad Laboratories, Hercules, Calif).

HISTOLOGIC ANALYSIS

Six eyes from 6 rats each in the statin-treated, L-NAME- and statin-treated, L-NAME–treated, vehicle-treated, and nonsurgically treated control groups were obtained to evaluate the severity of retinal damage. After 168 hours of reperfusion, the rats were euthanized with an overdose of anesthesia. The eyes were immediately enucleated, and a small incision was made at the corneoscleral limbus. These eyes were fixed in 2% formaldehyde and 2.5% glutaraldehyde in phosphate buffer, followed by 4% formaldehyde. They were then dehydrated, embedded in paraffin, sliced with a microtome into 2-mm-thick sections, and stained with hematoxylin-eosin. Each section was cut along the horizontal meridian of the eye through the optic nerve head perpendicular to the retinal surface.

To quantify the degree of retinal damage, changes in thickness and linear cell densities (number of nuclei in a 30-min wide band) within the various retinal layers were measured using the method described by Hughes, with slight modification. The thickness of the inner plexiform layer (IPL), inner nuclear layer (INL), outer nuclear layer (ONL), and overall retina from inner to outer limiting membrane (ILM-OLM) were determined. The number of cell nuclei in the ganglion cell layer (GCL) was also counted. These measurements were made at a distance of 1.5 mm from the center of the optic nerve head. The value was averaged from 5 measurements in the temporal and nasal hemispheres of 4 different sections.

STATISTICAL ANALYSIS

All values are presented as mean±SEM. The data were analyzed by 1-way analysis of variance using a post hoc test with the Fisher protected least significant difference procedure. Differences were considered statistically significant when P<.05.

RESULTS

EFFECTS OF STATIN ON LEUKOCYTE-ENDOTHELIAL INTERACTION

In all of the ischemic eyes examined, leukocytes were observed to roll slowly along retinal veins but not along any major retinal arteries (Figure 1A, left panel). No rolling of leukocytes along the major retinal veins was observed in nons ischemic control eyes (data not shown). The results for the leukocyte rolling are shown in Figure 1B. The number of rolling leukocytes in the pravastatin- and cerivastatin-treated rats was significantly reduced (by 10.8%; P<.001) (Figure 1A, right panel) compared with vehicle-treated rats (Figure 1B, left). The velocity of leukocyte rolling was significantly faster in statin-treated rats (P<.001) (Figure 1B, right).

The number of accumulated leukocytes was also significantly lower in pravastatin- and cerivastatin-treated rats than in vehicle-treated ones (Figure 2A). As presented in Figure 2B, the mean±SEM number of leukocytes accumulated in the retinal microcirculation in the statin-treated group 12 hours after reperfusion was 157.0±20.6 cells/mm², significantly fewer (by 30.6%; P<.001) than in vehicle-treated rats.

In parallel experiments, the short-term effect of cerivastatin (0.1 mg/kg) on the rolling and accumulation of leukocytes was examined 12 hours after reperfusion. Statin administered 15 minutes prior to the acridine orange injection did not significantly affect either rolling or accumulation (data not shown). Thus, this inhibitor might not have a direct short-term effect on the leukocyte-endothelial interaction.

GENE EXPRESSION OF P-SELECTIN AND ICAM-1 IN THE RETINA

To investigate the mechanism of statin-mediated inhibition of the leukocyte-endothelial interaction, we determined the expression levels of adhesion molecules in cerivastatin-treated and untreated rat retinas. As shown in

![Figure 1](image-url)

**Figure 1.** Effect of statin on leukocyte dynamics. A, Fluorescent fundus images 12 hours after reperfusion. Arrowheads point to rolling leukocytes along major veins. B, The number (left) and velocity (right) of rolling leukocytes were recorded along the major retinal veins after reperfusion. Values are presented as mean±SEM. Asterisks indicate control values. For each group, n=6.
To further investigate the protective effect of statin against retinal ischemia-reperfusion injury, we performed a quantitative histologic analysis (Figure 5A). Ischemia-reperfusion induction of the retina caused severe destruction of the inner retinal elements, resulting in decreased thickness and damage of the retinal cells. The thickness of the IPL, INL, and ILM-OLM in vehicle-treated rats (57.3%, 70.1%, and 75.0%, respectively, of that in nonsurgically treated rats) was significantly reduced (P<.001, P=.004, and P<.001, respectively). In addition, the cell density of the GCL in vehicle-treated rats (51.6% of that in nonsurgically treated rats) was significantly reduced (P<.001).

Destruction of the inner retinal elements was significantly suppressed in cerivastatin-treated rats compared with vehicle-treated rats. When treated with statin, the thickness of the IPL, INL, and ILM-OLM was 83.5%, 96.9%, and 92.2%, respectively, of that in nonsurgically treated rats (P<.001, P=.02, and P<.001, respectively, compared with vehicle- and surgically treated rats). The cell density of the GCL in statin-treated rats was 72.6% of that in nonsurgically treated rats (P<.001). Regarding the thickness of the OPL and ONL, there were no statistically significant differences among the 3 groups (nonsurgically treated, vehicle-treated, and statin-treated rats).

The observed protective effects of statin were reversed by intravenous injections of L-NAME, an NOS inhibitor. Although the administration of L-NAME alone
showed no significant effects compared with the vehicle-treated controls, simultaneous administration of statin and L-NAME resulted in a loss of the protective effects of statin. These data, together with the leukocyte rolling and accumulation results, indicate that statin exerts its protective effects on ischemia-reperfusion injury mainly by NO-dependent maintenance of endothelial functions.

To date, the mechanism of neuronal damage in retinal ischemia-reperfusion injury remains to be fully understood. Recently, considerable effort has been made to elucidate the neuropathy process, and an ischemia-reperfusion model of retinal circulation has been established. In such pathologic conditions, researchers have documented changes in endothelial function characterized by NO release and the endothelial interaction with leukocytes through leukocyte adhesion molecules. For instance, leukocyte adhesion molecules are reported to be up-regulated during short-term endothelial activation caused by ischemia-reperfusion induction. The resulting accumulation of leukocytes in posts ischemic tissues has also been implicated in the pathogenesis of ischemia-reperfusion injury by producing oxygen free radicals and releasing various cytokines. Manipulation of endothelial function may be a key in controlling the severity of the injury. In fact, a recent in vivo study from our laboratory using rats with ischemia-reperfusion injury showed that the reduction of leukocyte accumulation by inhibition of ICAM-1 and P-selectin markedly diminished the retinal damage from transient retinal ischemia.

In this study, we demonstrated that an HMG-CoA reductase inhibitor, pravastatin, associated with antigen 1 (LFA-1) and inhibited LFA-1–mediated leukocyte adhesion. However, LFA-1 may not play a major role in our study. Cerivastatin did not exhibit short-term effects against leukocyte dynamics, and pravastatin inhibited leukocyte-endothelial interaction in our experiments even without any inhibitory effect against LFA-1. It seems that statin acts via an enhanced release of NO from endothelial cells and suppressed induction of leukocyte adhesion molecules to ultimately decrease leukocyte accumulation and protect the subsequent retinal injury. Further experiments are needed to establish a causal relationship.

In addition, it is possible that the methods used in our study might induce a double injury to the retina, not only transient ischemia but also axotomy. With our methods...
ods, the blood flow is completely arrested by the liga-
ture of the optic sheath together with the intraorbital as-
pect of the optic nerve. It has been shown that axotomy
induces the loss of approximately 40% of the retinal GCL
population 7 days after its induction.37,38 In our study,
cell density of the GCL in vehicle-treated rats at 7 days
was 51.6% of that in nonsurgically treated rats. Al-
though our results are similar to the earlier reports of
axotomy, we think that the major retinal damage in this
study was related to the ischemia-reperfusion insult. A
previous study by Rosenbaum et al39 supports this con-
jecture: the degree of retinal injury at 7 days is similar in
2 models of retinal ischemia: high intraocular pressure
and suture ligature of the optic nerve. The retinal dam-
age and protective effects of statin in that study may be
due to several mechanisms. First, as discussed previ-
ously, the effective blocking of ischemia-induced leuko-
cyte-endothelial interactions and significant reduction of
adhesion molecule expression in the retina may result
in a positive neuroprotective effect via vascular action.

Second, the neuroprotective effect of statin may be re-
lated to several mechanisms, such as the inhibition of a
small GTPase family40 and attenuation of the inflamma-
tory cytokine responses that accompany insult in the neu-
ron,41 as was shown following cerebral ischemia. Al-
though illustration of the exact mechanisms awaits further
studies, our results do indicate the potential of statins as
novel neuroprotective drugs.

In conclusion, we have demonstrated that statin elic-
ts important neuroprotective effects in retinal ischemia-
reperfusion injury. The neuroprotective effects are NO-
dependent and are associated with the inhibition of leukocyte-endothelial interactions. Notably, systemic ad-
ministration of statin was sufficiently effective at the daily
clinical dose for hyperlipidemia. Statins may be devel-
oped into a valuable novel modality for neuroprotec-
tion in the retina.

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Figure 5. Light micrographs of the retina at a distance of 1.5 mm from the center of the optic nerve head. A, Representative result of nonsurgically treated control, vehicle-treated, cerivastatin-treated, nitroglycerine-nitro-L-arginine methyl ester (L-NAME)–treated, and L-NAME– and cerivastatin-treated rats (indicated by plus and minus signs) 168 hours after reperfusion. B, Number of cells and thickness of different retinal layers 168 hours after reperfusion. Data are expressed as a percentage of nonsurgically treated control rats. Values are presented as mean ± SEM. Asterisks indicate P < .05; double asterisk indicates P < .005.
REFERENCES


