Retinal Ganglion Cell Apoptosis in Glaucoma Is Related to Intraocular Pressure and IOP-Induced Effects on Extracellular Matrix

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PURPOSE. To investigate the effect of IOP on retinal ganglion cell (RGC) apoptosis and correlate the effects with IOP-induced changes in extracellular matrix (ECM) in the retina and optic nerve head (ONH) in glaucomatous rat eyes.

METHODS. Thirty-seven Dark Agouti rats had elevated IOP induced in the left eye by hypertonic saline episcleral vein injections. Eyes were examined at 3 months histologically for RGC apoptosis and expression of specific ECM components.

RESULTS. RGC apoptosis was significantly related to IOP exposure (integral ΔIOP P < 0.001; peak IOP P < 0.01). In the RGC layer, elevated IOP correlated positively to a significant increase in MMP-9 activity (P < 0.001), tissue inhibitor of matrix metalloproteinase (TIMP-1) (P < 0.05), and collagen I (P < 0.01), and negatively correlated to deposition of laminin (P < 0.05) and TGF-β2 (P < 0.05). There was a significant correlation between MMP-9 activity and both RGC apoptosis (P < 0.001) and loss of laminin (P < 0.01). IOP exposure was also associated with increased deposition of TGF-β2 and collagen I at the ONH (P < 0.01).

CONCLUSIONS. The results demonstrated that RGC apoptosis in glaucoma correlates strongly with elevated IOP and is significantly associated with IOP-induced changes in specific ECM components in the RGC layer. The study shows for the first time a link between MMP-9, laminin degradation, RGC apoptosis, and IOP exposure in glaucoma. The findings suggest that abnormal ECM remodeling in the glaucomatous retina may relate to RGC death and support the notion that the retina is a primary site of injury in glaucoma. (Invest Ophthalmol Vis Sci. 2005;46:175–182) DOI:10.1167/iovs.04-0832

Glaucoma is a major cause of worldwide irreversible blindness. Vision loss in glaucoma is attributed to retinal ganglion cell (RGC) death, and intraocular pressure (IOP) is the major modifiable risk factor. The underlying mechanisms that link elevated IOP to glaucomatous RGC death are not fully understood, though the process of RGC apoptosis is heavily implicated. Furthermore, the site of primary damage in glaucoma is controversial, although it is suspected to be either at the optic nerve head (ONH) or the retina and is complicated by the likelihood of the effects of secondary RGC degeneration.

An established theory is that elevated IOP induces physical changes at the ONH, visualized clinically as optic disc cupping, which causes optic nerve axonal compression at the lamina cribrosa, blockage of axoplasmic flow, and interference in retrograde neurotrophin transport to RGCs, leading to cell death. The ONH has previously been investigated in both human and experimental animal models as a primary site of glaucomatous damage. These studies have shown extensive remodeling of the extracellular matrix (ECM), including collagen I and IV, TGF-β2, and matrix metalloproteinase (MMP)-1. Hernandez has identified the astrocytes as the key cell type involved in this process at the ONH and has shown astrocytes to be activated by increased IOP. Yan et al. have shown that these active astrocytes are responsible for the production of the matrix-degrading enzymes (MMPs) that affect the pattern of matrix remodeling. It is believed that these effects are modulated by astrocyte production of TGF-β2, which has been shown to be significantly increased in the glaucomatous ONH.

Previous studies have shown a positive correlation of the loss of RGC axons to the level of IOP elevation in experimental rat glaucoma. It is estimated that approximately half of the total RGCs are lost after 2 to 3 months of IOP elevation. However, there has been little research on the direct effect of IOP on RGC apoptosis, although recent in vitro studies suggest RGC apoptosis may be induced directly by elevated IOP, supporting the theory that the retina is the primary injury site in glaucoma.

The mechanisms by which RGC apoptosis occurs have recently been linked to specific ECM-related changes in MMP-9 and laminin expression in the retina. This is further corroborated by the fact that in the central nervous system (CNS), neuronal apoptosis is associated with increased MMP-9 activity.

We have investigated for the first time, as far as we are aware, the effect of IOP elevation on the level of RGC apoptosis in an in vivo model of glaucoma. As RGC apoptosis has been recently linked to specific ECM changes, we have evaluated the role of MMP-9, laminin, and TIGF-1 activity in the retina, and whether RGC apoptosis is at all related to IOP-induced effects on these targets. In addition, we have assessed the effects of IOP on changes in collagen I, IV, MMP-1, and TGF-β2 at both the ONH and retina.

METHODS

Animals

Adult male Dark Agouti (DA) rats, weighing 200 to 300 g, were treated with procedures approved by the UK Home Office and in compliance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research.
Experimental Rat Model of Glaucoma

Thirty-seven DA rats, were anesthetized by intraperitoneal injections of ketamine (37.5 mg/kg) and xylazine (25 mg/kg). After anesthesia, the rats were placed in a stereotactic frame and a small incision was made in the right eyelid. The anterior chamber was then cannulated with a 20-gauge needle, and a small amount of balanced salt solution was injected to flush saline from the anterior chamber. A 27-gauge needle was then inserted into the anterior chamber and the needle was advanced until it reached the vitreous space. The needle was then removed, and the anterior chamber was reconstituted with balanced salt solution. The incision was then closed with suture. Following surgery, the rats were placed in a heated environment to maintain body temperature. The rats were allowed to recover for 24 hours before the experiment was performed.

IOP Measurements

The IOP of each eye was measured using a tonometer. The tonometer was placed on the cornea of the eye and the reading was taken. The IOP was measured just before and after each injection of fluid. The average IOP was calculated for each condition.

Identification of Retinal Ganglion Cells

So as to identify RGCs unequivocally, a subgroup of rats (n = 12) had RGCs retrogradely labeled by the application of DiAsp/4-(dicyethylamino)styryl)-N-methylpyridinium iodine (Di-4Di-10-Asp; Molecular Probes-Cambridge Biosciences, Cambridge, UK) to both superior colliculi. The Binding Site, Ltd.), mouse anti-TIMP-1 (1:20; R&D Systems, Abingdon, UK), rabbit anti-laminin (1:60; Chemicon International, Temecula, CA), rabbit anti-4-Di-10-Asp antibodies (Molecular Probes-Cambridge Biosciences, Cambridge, UK) to both superior colliculi.

Assessment of Retinal Ganglion Cell Apoptosis

To assess RGC apoptosis, fluorescent Alexa-488-labeled annexin V (1.25 μg in 5 μL) was injected into the vitreous of both eyes of the rats. The flat retinas labeled with annexin V were processed for frozen or paraffin-embedded sections. Sections were stained with red dye (Vector Red; Vector Laboratories, Burlington, CA) or diaminobenzidine (DAB) and counterstained with hematoxylin.

Sections were processed for staining by two independent and masked observers who used a grading system and analysis method well known to our group. For staining, the retinas were incubated with anti-MMP-9 antibody and annexin V, were counted.
labeled by annexin V (green), RGCs labeled by DiAsp (red),
and retinal nuclei stained with DAPI (blue). Localization of
apoptosis to the RGC layer was confirmed by double staining
of cells with annexin V and DiAsp (Figs. 1A, 1B) and with
annexin V and DAPI in a retinal wholemount (Fig. 1C) and
cross sections (Fig. 1D).

In normal control eyes, we found the mean number of RGCs
to be 115,000 ± 2,021. We demonstrated RGC apoptosis in all
eyes. The mean number of apoptotic RGCs in control eyes was
324.50 ± 49.93, compared with 1516.22 ± 308.91 in surgical
eyes. Compared with control eyes, the number of apoptotic
RGCs was significantly higher in all glaucomatous eyes at 3
months after surgery (t-test, P < 0.001). We found a significant
correlation of RGC apoptosis with integral IOP (Pearson’s,
r = 0.766, P < 0.001; Fig. 2A) and peak IOP (Pearson’s r =
0.533, P < 0.01; Fig. 2B).

For the RGC counts at 3 months after elevation of IOP, the
mean percentage loss of RGCs was 61.21% ± 7.54%. Again, we
found a significant correlation between RGC loss and integral
IOP (Pearson’s r = 0.777, P < 0.005; Fig. 2C) and peak IOP
(Pearson’s r = 0.612, P < 0.05; Fig. 2D).

IOP-Induced ECM Changes in Retina and ONH

Compared with control eyes, we found a decrease in laminin
deposition in the RGC layer in all IOP-elevated eyes and
showed a significant negative correlation with IOP integral
(Pearson’s r = -0.661, P < 0.05; Figs. 3A, 3C, 3E). We also
found an increase in TIMP-1 immunolabeling in IOP-elevated
eyes and showed a significant correlation with IOP exposure
(Pearson’s r = 0.605, P < 0.05; Figs. 3B, 3D, 3F), but no
change in MMP-1. We demonstrated a significant increase in
collagen I deposition (Pearson’s r = 0.778, P < 0.01) in the
RGC layer with elevated IOP, but not in collagen IV. In addition,
TGF-β2 labeling showed a decrease in the RGC layer, and

FIGURE 1. RGC apoptosis was detected in all rat eyes, although it was
considerably greater in glaucomatous retinas. Immunohistochemistry
confirmed that apoptotic cells were localized to the RGC layer (RGCL).
Typical fluorescence micrographs from the control eye (A) and the
contralateral, IOP-elevated eye (B–D) show apoptotic cells stained by
Alexa-488–labeled annexin V (green) and RGCs labeled by DiAsp (A,
B, red), with DAPI as a nuclear stain (C, D, blue), both in retinal
wholemounts (A–C) and cross sections (D). INL, inner nuclear layer.
Scale bars, 15 μm.

FIGURE 2. RGC apoptosis correlated positively with both ΔIOP integral
(A) and peak IOP (B) (Pearson’s r = 0.766 and 0.533, P < 0.001
and < 0.01, respectively). Similarly, there was a significant correlation be-
tween the percentage loss of RGCs and ΔIOP integral (C) and peak IOP
(D) (Pearson’s r = 0.777 and 0.612, P < 0.005 and < 0.05, respectively).
again, the change was significantly correlated with integral ΔIOP (Pearson’s r = –0.625, P < 0.05).

We demonstrated intense MMP-9 immunofluorescence localized to the RGC layer compared with control eyes. The pattern of staining was discontinuous, with areas of skip lesions. Figure 4 illustrates MMP-9 (Fig. 4A, blue) colocalizing to apoptotic cells stained with Alexa-488–labeled annexin V (Fig. 4B, green) and RGCs and axons labeled by NF-200 (Fig. 4C, red). There was a very strong correlation between the mean grade of MMP-9 immunostaining and integral ΔIOP (Pearson’s r = 0.898, P < 0.00; Fig. 5A) and peak IOP (Pearson’s r = 0.721, P < 0.01; Fig. 5B). Furthermore, MMP-9 immunoreactivity was significantly related to a decrease in laminin deposition (Pearson’s r = –0.726, P < 0.01; Fig. 5C) and an increase in the number of apoptotic RGCs (Pearson’s r = 0.898, P < 0.001; Fig. 5D).

For the ECM components in the ONH, we demonstrated an increase in TGF-β2, collagen I, collagen IV, and MMP-1 in all glaucomatous compared with control eyes. TGF-β2 was identified mainly in the transition region of the ONH (Figs. 6A, 6B) whereas collagen IV was deposited throughout the ONH. However, only TGF-β2 and collagen I deposition appeared to correlate significantly with ΔIOP integral (Pearson’s r = 0.688, 0.686, respectively, P < 0.01; Figs. 6C, 6D). There were no significant difference between glaucomatous and control eyes, in collagen IV (Pearson’s r = 0.357, P = 0.345) and MMP-1 (Pearson’s r = 0.446, P = 0.170) staining. Histology demonstrated changes in the ONH contour in glaucomatous com-

**Figure 3.** Immunohistochemistry on paraffin-embedded cross sections shows typical staining in control (A, B) and glaucomatous (C, D) eyes of laminin (A, C) and TIMP-1 (B, D). Insets: Same cross section of retina at low magnification. Immunostaining demonstrated a decrease in laminin (C) and an increase in TIMP-1 (D) in all glaucomatous eyes compared with the control. On analysis, loss of laminin (E) and increased TIMP-1 expression (F) correlated significantly with ΔIOP integral (Pearson’s r = –0.661 and –0.605, respectively, P < 0.05). Scale bars, 10 μm.
pared with control eyes, including scleral canal expansion or cupping with loss of nerve fibers (Figs. 6E, 6F).

DISCUSSION

In this study RGC apoptosis correlated significantly with IOP exposure in a rat model of glaucoma. Elevated IOP was significantly positively related to expression of MMP-9, TIMP-1, and collagen I in the RGC layer—the first time this has been shown. In contrast, it correlated negatively with laminin and TGF-β2. The level of RGC apoptosis correlated significantly to MMP-9 activity, suggesting that this may be an important mechanism mediating glaucomatous RGC loss. The results also confirmed that TGF-β2 and collagen I deposition correlates significantly with raised IOP at the ONH.

RGC death in experimental glaucoma has been shown to occur by the process of apoptosis. Our data demonstrated that RGC apoptosis correlated positively with both ΔIOP integral and peak IOP in the rat model, supporting the theory that the level of IOP elevation determines the extent of RGC loss. Although our incidence of apoptosis was similar to that reported in previous studies (0.5%–3.0% of the total population of RGCs; normal RGC count in our model, 115,000 cells or 2,213 cells/mm²), it was higher than recorded in studies in which TUNEL was used as the method of detection. This discrepancy may be due first, to the increased identification of positive cells with annexin V, and also because of its administration before the animal was killed. Compared with TUNEL, which detects mainly the DNA fragmentation phase of the pathway (representing only a small fraction of cells undergoing apoptosis at any single time point), annexin V detects translocated membrane phosphatidylserine (PS), which occurs from an early stage and during a major part of the process of apoptosis. Even so, the number of dying RGCs labeled by annexin V was still lower than that previously defined by light microscopy by Quigley et al. (10% of ganglion cells).

Several studies have investigated RGCs or their axonal loss after experimental IOP elevation in the rat. There is a suggestion that RGC death after IOP elevation occurs in two phases: the fast phase, occurring in the initial 3 weeks with a rate of 12% RGC loss per week, followed months later by a second, slow-phase rate of 2%. The mechanism in the early phase may be pressure related, with recent evidence of neuronal cells undergoing apoptosis within 2 to 20 hours after being subjected to elevated IOP. The second phase, occur-

![Figure 4](image1.png)

**FIGURE 4.** Immunohistochemistry of frozen cross sections illustrated MMP-9 (A, blue) colocalizing to apoptotic cells in the RGC layer stained with Alexa-488-labeled annexin V (B, green) and RGCs labeled with NF-200 (C, red). (D) Composite image and low-magnification (inset) demonstrated discontinuity in MMP-9 immunostaining with areas of skip lesions. Bar, 10 μm.

![Figure 5](image2.png)

**FIGURE 5.** Increase in MMP-9 immunoreactivity in glaucomatous eyes was strongly positively correlated with ΔIOP integral (A, Pearson’s r = 0.898, P < 0.001) and peak IOP (B, Pearson’s r = 0.721, P < 0.01). A correlation between MMP-9 upregulation and a decrease in laminin immunostaining in the RGC layer was also demonstrated (C, Pearson’s r = -0.726, P < 0.01), as also a direct relationship between MMP-9 and the number of apoptotic RGCs (D, Pearson’s r = 0.898, P < 0.001).
ring a month or so after elevated IOP, is also believed to involve apoptosis but through the process of secondary degeneration—a process that causes the death of RGCs that survive the primary insult but are injured by toxic effects of the primary degenerating neurons. This may explain the lag period between RGC apoptosis and the initial event of IOP elevation. RGC and axonal loss has been estimated to be \( \geq 50\% \) at 2 months after IOP elevation, similar to our own findings. Compared with previous work which concentrated on the absolute reduction of RGC counts, in this study, we labeled and counted apoptotic cells throughout the whole retina, and then analyzed RGC attrition as a function of IOP exposure. As far as we know, this has not been investigated before.

The persistence of RGC apoptosis above baseline levels at 3 months after surgery supports a cumulative effect of IOP over time. This effect has been observed by other investigators who have shown a significant positive correlation of \( \Delta IOP \) integral with the percentage of axonal loss occurring in glaucomatous rats. The mechanisms of this effect are still not established. One possible explanation is that ONH remodeling is still occurring at 3 months in this model, as confirmed by an increase in TGF-\( \beta 2 \) and collagen I immunoreactivity in this study, and this causes RGC axonal compression. In addition, the surviving axons may still be susceptible to the cumulative effect of IOP elevation.

A possible new mechanism by which RGC apoptosis actually occurs in relation to IOP exposure at the site of the retina highlighted in this study, is the association of ECM changes in the retina, in particular, the strong correlation of MMP-9 expression in RGCs with IOP exposure and RGC apoptosis. It is possible that IOP-induced changes in specific ECM components or cytokines in the retina contribute to an increase in MMP-9 activity. There is accumulating evidence that changes in
the status and composition of the ECM affect the function of a variety of different cells and modulate the synthesis and release of MMPs and vice versa.\textsuperscript{31-32} An in vitro study has recently shown that specific matrix components, including fibronectin, collagen I and IV, induce an increase in MMP-2 and -9 from human glomerular mesangial cells.\textsuperscript{52} In addition, ECM provides adherence signals that control cell function and survival.\textsuperscript{31} Changes in specific ECM components can interrupt cell–cell and cell–ECM interactions, leading to cell death.

Our finding that enhanced MMP-9 activity in apoptotic RGCs paralleled the decreased deposition of laminin in the RGC layer suggests increased degradation of the ECM at the retinal site in response to IOP exposure. Laminin is an ECM component believed to facilitate cell attachment and survival.\textsuperscript{53} If cells begin to secrete large amounts of proteases (such as MMP-9) it is only logical that ECM components such as laminin may disappear. As laminin may provide survival signals through interactions with cellular integrins, the reduction or lack of laminin may lead to the interruption of cell–ECM communication making cells more susceptible to apoptosis, or anoikis (the form of apoptosis caused by lack of substrate-derived survival signals).\textsuperscript{55} In support of our finding, MMP-9 activity has been linked to neuronal cell death in brain injury or ischemia.\textsuperscript{22,34,35} Moreover, brain neuronal death is associated with loss of laminin\textsuperscript{56} and MMP-9 expression. Recently, MMP-9-deficient mice have been demonstrated to have reduced RGC loss as a result of limited laminin degradation in a model of optic nerve ligation and RGC death.\textsuperscript{20} This same group has subsequently demonstrated a correlation between MMP-9 up-regulation and a decrease in laminin immunostaining in the RGC layer.\textsuperscript{21,35} Our study demonstrates for the first time a link between MMP-9, laminin degradation, RGC apoptosis, and IOP exposure in glaucoma.

The interpretation of our observations is that retinal cells, possibly RGCs, increase secretion of MMP-9 as a direct response to raised IOP, and that this in turn leads to MMP-9-induced loss of laminin and consequently, RGC apoptosis. This notion supported by previous findings from Chuntestal et al.\textsuperscript{20} and Zhang et al.\textsuperscript{21} However, our data do not exclude the possibility that the mechanical effect of elevated IOP could cause RGC axonal damage in the region of the ONH, leading to retrograde damage of the RGC cell body, which in turn may induce an increase in MMP-9 activity, resulting in the changes in the ECM. An alternative theory for IOP inducing an increase in MMP-9 expression could be that it is an indirect effect mediated by glutamate—a major excitatory neurotransmitter. Glutamate appears to be increased by different types of stimuli, including injury, ischemia, and elevated IOP.\textsuperscript{36-40} Glutamate is known to be involved in the activation of MMP-9, with the demonstration of MMP-9 mRNA and protein being up-regulated by the glutamate receptor agonist, kainite, in rat hippocampus.\textsuperscript{41} Furthermore, a recent study has demonstrated that activation of retinal glutamate receptors upregulates MMP-9. This upregulation has been attributed to the development of laminin loss and retinal degeneration in this model,\textsuperscript{42} and suggests that any insult leading to glutamate-mediated activation of MMP-9 could lead to RGC apoptosis.

Along with an increase in MMP-9 activity, we also showed an increase in TIMP-1 in the RGC layer, correlated with the degree of IOP exposure. In a previous study, both MMP-9 and TIMP-1 were shown to be induced in ischemic rat brain, regulated in a cell- and time-dependent manner in association with neuronal death.\textsuperscript{22} TIMP-1 is usually recognized as an inhibitor for MMPs, specifically MMP-9, to maintain ECM homeostasis.\textsuperscript{42} Therefore, the increase in TIMP-1 may serve to counterbalance the simultaneous increase in MMP-9.\textsuperscript{43} However, recent studies have shown that TIMP-1 has neuroprotective effects that are independent of its ability to inhibit MMPs.\textsuperscript{44} In normal conditions, RGCs express significant levels of TIMP-1, but low constitutive levels of MMP-9.\textsuperscript{30,37,45} The increase in retinal TIMP-1 demonstrated in this study is likely to facilitate its neuroprotective effect on RGCs through both inhibition of MMP-9 and antiapoptotic actions. This would be in keeping with the theory that ECM remodeling continuously occurs in the retina after exposure to raised IOP.

Our analysis of changes in ECM at the ONH site is consistent with previous studies.\textsuperscript{61,46} We demonstrate a clear relationship between TGF-β2 deposition and IOP exposure, supporting the previous observations implicating the association of TGF-β2 with ONH changes in ECM in glaucoma.\textsuperscript{12,15} The increased expression in TGF-β in the ONH may be as a stress response to raised IOP, in that TGF-β has been highlighted as a key molecule stimulated by mechanical stress.\textsuperscript{47} In contrast to the ONH, we found a significant reduction in TGF-β2 deposition in the retina with increased IOP exposure. TGF-β is one of the most potent modulators of wound healing throughout the body.\textsuperscript{13} Given that TGF-β2 is a major stimulant of ECM and an inhibitor of MMPs, it may not be surprising that the low level of TGF-β2 in the retina is associated with increased activity in MMP-9 and decreased deposition in laminin. One study has shown that a decrease in TGF-β and an increase in MMPs are associated with vascular cell apoptosis.\textsuperscript{48} It is well established that the effects of TGF-β are cell specific and concentration dependent, with different functions being maximally stimulated at different concentrations.\textsuperscript{49} The biphasic behavior of TGF-β may offer an alternative explanation to why we found low levels of TGF-β2 in the RGC layer and high levels in the ONH and why both may be associated with increased levels of RGC apoptosis.

Taken together, our observations have demonstrated that RGC apoptosis in glaucoma correlates strongly with IOP exposure and that RGC apoptosis is significantly related to specific IOP-induced changes in ECM components. Our data suggest that the retina may be the primary site of injury in glaucomatous neuropathy and implicate MMP-9 activity as being involved in the development of RGC apoptosis in glaucoma. To the best of our knowledge, this is the first report of RGC apoptosis in relation to ECM remodeling.

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References

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