Cyclooxygenase-2 in Human and Experimental Ischemic Proliferative Retinopathy

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Background—Intravitreal neovascular diseases, as in ischemic retinopathies, are a major cause of blindness. Because inflammatory mechanisms influence vitreal neovascularization and cyclooxygenase (COX)–2 promotes tumor angiogenesis, we investigated the role of COX-2 in ischemic proliferative retinopathy.

Methods and Results—We describe here that COX-2 is induced in retinal astrocytes in human diabetic retinopathy, in the murine and rat model of ischemic proliferative retinopathy in vivo, and in hypoxic astrocytes in vitro. Specific COX-2 but not COX-1 inhibitors prevented intravitreal neovascularization, whereas prostaglandin E₂, mainly via its prostaglandin E receptor 3 (EP₃), exacerbated neovascularization. COX-2 inhibition induced an upregulation of thrombospondin-1 and its CD36 receptor, consistent with the observed antiangiogenic effects of COX-2 inhibition; EP₃ stimulation reversed effects of COX-2 inhibitors on thrombospondin-1 and CD36.

Conclusion—These findings point to an important role for COX-2 in ischemic proliferative retinopathy, as in diabetes.

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Key Words: prostaglandins ■ diabetes mellitus ■ ischemia ■ vasculature

Intravitreal neovascularization, which characterizes diabetic retinopathy, retinopathy of prematurity, or retinal vein occlusion, is a major cause of blindness.¹ Retinal ischemia is a common precursor to vitreal neovascularization in retinal diseases² and is associated with a local inflammatory response in the ischemic retina.³ Early proinflammatory genes are expressed in ischemic disorders. We have recently shown that inducible NO synthase contributes to the development of intravitreal neovascularization⁴ and to retinal apoptosis and degeneration.⁵

Cyclooxygenase (COX)-2 is also an immediate-early gene product of inflammation.⁶ Prostanoids are synthesized principally via activities of COX-1 and COX-2. COX-1 is mostly constitutive and is expressed in most tissues. COX-2 is induced by cytokines, mitogens, and endotoxins, accounting for elevated prostaglandin production during inflammation.⁶ COX-2 can be expressed developmentally and on ischemic stimuli in retina.⁷ COX-2 exerts an angiogenic effects in tumors⁸ and in corneal neovascularization.⁹ It has also been shown that prostanoids, notably prostaglandin E₂ (PGE₂), stabilize the hypoxia-inducible factor¹¹ and stimulate expression of basic regulators of angiogenesis, including vascular endothelial growth factor (VEGF) in tumor endothelium,¹² resulting in endothelial cell proliferation.¹² We hereby investigated the role of COX-2 in a nontumoral condition, namely ischemic proliferative retinopathy, using human retinal tissue and experimental proliferative ischemic retinopathy. Our findings disclose an important role for this immediate-early gene product in proliferative retinopathy mediated (at least in part) by PGE₂ mostly via prostaglandin E receptor 3 (EP₃) through a previously undescribed action involving thrombospondin-1 (TSP-1) and CD36.

Methods

Human Samples
The eyes from 7 postmortem humans with diabetes mellitus, 4 eyes from 4 postmortem humans with no history of diabetes or ocular disease, and the ipsilateral eye from 1 subject with ocular ischemic syndrome secondary to severe carotid artery obstruction (case 12) were obtained.
Animal Models of Ischemic Proliferative Retinopathy

All procedures were conducted in accordance with the Association for Research in Vision and Ophthalmology’s statement, *The Use of Animals in Ophthalmic and Vision Research.*

In the murine model, C57BL/6 mice at postnatal day (P) 7 were exposed, with their mothers, for 5 days to hyperoxic conditions (75% O₂) inducing vaso-obliteration of the central retinal vasculature. At P12, mice were returned to room air; extensive vitreal neovascularization was present in all mice, with the maximum effect observed on P17. Ischemic proliferative retinopathy was also reproduced in Sprague-Dawley rats exposed to 7 cycles of hyperoxia (80% O₂, 20.5 hours) and hypoxia (10% O₂, 0.5 hours) with a gradual return to 80% O₂ over 3 hours, from P1 to P7. Thereafter, rats were returned to room air, and neovascularization was evaluated at P12.

Mice and rats were anesthetized with an intraperitoneal injection of a ketamine (100 mg/kg) and xylazine (15 mg/kg) solution and intravitreally injected using glass capillaries (~60 gauge). Right eyes of mice were injected intravitreally at P13 and P15 with 0.5 μL of vehicle (50% polyethylene glycol [Sigma-Aldrich], 40% PBS, and 10% ethanol); 2, 10, or 50 μM/L of specific COX-2 inhibitor o-acetoxysphingosine (APHS, Calbiochem) (n=16/group); or 0.3 μM/L 16,16-dimethyl-PGE₂ (Sigma-Aldrich), resulting in estimated effective vitreal concentrations of drugs (estimated total eye volume of 10 μL based on spheric volume and volume-to-weight ratio calculation) of 0.2, 1, and 5 μM/L (APHS and SC-560) and 0.03 μM/L (16,16-dimethyl-PGE₂). Eyes were enucleated at P17 and subjected to retinal histochemistry (n=8) and intravitreal neovascularization quantification (n=8) (see below). Rat pups (n=8 to 13/group) were injected in the right eye at P7 and P9 with either 1 μL of vehicle (NaCl 0.9%) or the selective COX-2 inhibitor etodolac 40 μM/L (Sigma-Aldrich), with or without 16,16-dimethyl-PGE₂, 4 μM/L (Cayman Chemicals), a specific EP₂, EP₃ agonist, respectively, butaprost 400 μM/L (Cayman Chemicals) or M&B28767 4 μM/L (Rhone-Poulenc Rorer), to obtain estimated effective vitreal concentrations of drugs (estimated total eye volume of 40 μL) of 1 (etodolac), 0.1 (16,16-dimethyl-PGE₂), 10 (butaprost), and 0.1 (M&B28767) μM/L; EP₂ and EP₃ receptor agonists were used because antagonists are not readily available. Rats were euthanized at P12 and retinas stained for endothelial cells and flat mounted (see below).

Immunohistochemistry

Human and murine eyes were fixed in 4% paraformaldehyde and embedded, sectioned (5 μm), and deparaffinized. Sections were stained using a heat-induced antigen retrieval and a 3-step avidin-biotin complex technique using avidin–alkaline phosphatase or avidin-FITC as previously described. Antibodies used were polyclonal COX-2 antibody (Biomol Laboratories and Cayman Chemical Co), monoclonal EP₂ antibody (generous donation by Exalpha Biologicals), monoclonal glial fibrillary acidic protein (GFAP) (Oncogene), and TRITC-conjugated lectin griffonia simplicifolia (Sigma-Aldrich).

Cell Culture

Given the need for sufficient tissue quantities, primary astrocyte and endothelial cell cultures were obtained for practical reasons from neonatal porcine retinas; cells from this species respond to a variety of stimuli implicated in ischemic retinopathies in the same manner as that of rodent tissues. Neonatal porcine retinal astrocytes were isolated as described for brain astrocytes. Cells of the third to fourth passages were used. Cultures were ~95% GFAP positive. Monolayers (80% confluent) of astrocytes were incubated at 37°C either under normoxic (95% air; 5% CO₂) or hypoxic conditions (2% O₂, 5% CO₂, 93% N₂) for 24 hours. Subsequently, the medium was changed and cells were incubated for 1 hour in the presence of APHS (1 μM/L), etodolac (1 μM/L), SC-560 (0.2 μM/L), or etodolac (1 μM/L) and SC-560 (0.2 μM/L); drug concentrations used were equivalent to those estimated in vivo. PGE₂ concentrations were measured in the supernatant, and the cells were harvested for protein quantification and Western blot analysis. The pH of the medium was unchanged during 24-hour hypoxia. For endothelial cell culture, newborn porcine neuroretinal microvessels were isolated as previously reported.

Western Blot

Protein extraction of cells was performed as previously described. Rat retinas were pooled and membranous and cytosolic fractions were separated as previously described. Antibodies used were polyclonal anti-COX-2 (Cayman); polyclonal anti-COX-1 (Santa Cruz Biotechnology); mouse monoclonal EP₂, EP₃, and EP₄ (Exalpha Biologicals); polyclonal anti-VEGF antibody (Chemicon); rat monoclonal anti–VEGF receptor (VEGFR)–2 (Chemicon); monoclonal anti–TSP-1 (Oncogene); polyclonal purified anti-CD36; monoclonal 

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<th>Subject Characteristics and Results of COX-2 Staining</th>
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DM indicates diabetes mellitus; IDDM, insulin-dependent diabetes mellitus; NIDDM, non–insulin-dependent diabetes mellitus; NFL, nerve fiber layer; M, male; and F, female.
anti-clathrin (Transduction Laboratories, BD Biosciences); monoclonal anti–β-actin (Novus Biological); and monoclonal GFAP (Onco- gene). Western blots were performed on equal amounts of proteins as described.18

**PGE2 Radioimmunoassay**
PGE2 concentrations in retinal tissue (n=3 per group) and astrocyte supernatant were determined as previously described.22

**RNA Isolation and Reverse Transcription–Polymerase Chain Reaction (PCR) Analysis**
Retinal mRNA expression from whole retinal extracts (n=3 per group) was analyzed using reverse transcription–PCR (cycles below the saturating conditions) as previously described.4 Oligonucleotide primers were the following: for COX-2, antisense 5'-GGAGAAGGCTCCAGCTTTTG-3', and sense 5'-GCAAATCTCCTGCTGTCCAATC-3', resulting in a PCR product of 336 bp; for actin, antisense 5'-GTCATGCCC-GATAGTGACCT-3', and sense 5'-GGTTGGGATGCGGTCAGAGGA-3', resulting in a 630-bp PCR product.

**Quantification of Vitreal Neovascularization and Intraretinal Revascularization**
Mouse eyes were paraffin embedded, cut sagitally (parallel to the optic nerve), and stained with periodic acid-Schiff and Hemalun. Vitreal neovascularization (vascular cell nuclei found on the vitreal side of the inner limiting membrane) was counted by blinded investigators as previously described.7 Neovascular nuclei were absent in animals raised in room air. Intraretinal vasculature was visualized on retinal flat mounts stained with TRITC-conjugated lectin griffonia simplicifolia (Sigma-Aldrich),23 and the surface of the capillary free area measured using a computerized image-analysis system (Scion Image). In the rat model, intravitreal neovascularization was evaluated by counting intravitreal neovascular tufts on lectin-stained retinal flat mounts.

**Statistical Analysis**
Results are expressed as mean±SEM. Statistical analyses were performed using the Mann-Whitney test and ANOVA. Statistical significance was set at P<0.05.

**Results**

**COX-2 Expression in Human Diabetic Retina**
Patient characteristics are summarized in the Table. COX-2 immunoreactivity was observed in all eyes in the retinal pigment epithelial cells, in the outer segment of the photoreceptors and to some degree in the inner plexiform layer (data not shown). In all diabetic subjects, COX-2 immunoreactivity was also detected in the nerve fiber layer (NFL) (Figure 1a, cases 1 to 7); this COX-2 immunostaining was granular and discontinuous. COX-2 immunolocalization was positive) (Figure 3e and 3f).

**COX-2 Expression and Localization, and PGE2 Concentrations in Experimental Ischemic Retinopathy**
COX-2 expression is altered by ischemia in neural tissue.24 We explored the involvement of COX-2 in a murine model of retinopathy of prematurity. Equivalent COX-2 mRNA expression was observed in room air and after hyperoxia exposure at P12, P14, and P17 (Figure 2A). Immunolocalization of COX-2 was studied in mouse retina and was found to be similar to that in humans. In normoxic mice at P14, COX-2 protein was robustly expressed in retinal pigment epithelial cells both in the outer photoreceptor segment and in the inner plexiform layer (data not shown). In the post–hyperoxia-exposed retinas, COX-2 expression was also detected in the NFL at P14 (Figure 3a) predominantly in astrocytes (GFAP positive) (Figure 3e and 3f).

COX-2 protein expression was evaluated in membrane fractions of retina extracts from hyperoxia-exposed rats. At the end of the hyperoxic period (P1 through P7), COX-2 immunoreactivity diminished and tended to increase in the early hours after resuming exposure to room air (24 hours after hyperoxia; Figure 2C). COX-1 exhibited the reverse pattern, and consequently whole retina concentrations of PGE2, a mediator involved in angiogenesis,25 were unaltered during the posthyperoxia period (Figure 2B); although this does not exclude a local paracrine effect of this autacoid. Consistent with these observations, primary retinal astrocyte cultures exposed for 24 hours to relative hypoxia (2% O2, 5% CO2, 93%) exhibited increased COX-2 expression (Figure 2D) and PGE2 levels (Figure 2E) compared with those in normoxia (95% air, 5% CO2), whereas COX-1 expression remained steady. Specific COX-2 inhibitors, APHS and etodolac, markedly dimin-

![Figure 1. COX-2 immunohistochemistry on human retinas of diabetic (a and c through e) and nondiabetic (b and f through h) subjects. Shown is colocalization of GFAP and COX-2 in nondiabetic (f through h) and diabetic (c through e) eyes. Panel heights are 240 μm (a and b) and 90 μm (c through h). NFL indicates nerve fiber layer; INL and ONL, inner nuclear layer and outer nuclear layer, respectively.](Image 314x449 to 548x726)
ished PGE₂ levels, whereas COX-1–selective SC-560 only
caused a small decrease in PGE₂ concentrations (Figure
2E) even at highest dose tested (5 μmol/L), suggesting a
dominant role for COX-2 in PGE₂ generation during
hypoxia.

In age-adjusted normoxic whole retinas, COX-1 and -2
expression did not change. Immunolocalization of COX-2 in
rat retina was similar to that observed in mouse (data not
shown).

**COX Inhibition in Ischemic Proliferative Retinopathy**

The impact of COX inhibition on neovascularization was
tested using specific COX-2 (APH5 and etodolac) and
COX-1 (SC-560) inhibitors; concentrations corresponded to
effective ones on astrocyte PGE₂ levels (Figure 2E). In vivo,
posthyperoxia administration of the preferential COX-2 in-
hibitor APHS did not affect the degree of capillary-free area

or the intraretinal revascularization of the ischemic retina
studied 4 days after the first dose (P17) (Figure 4A and 4B).
However, intravitreal neovascularization (revealed by intrav-
itreal vascular nuclear counts) was dose-dependently dimin-
ished by APHS, whereas the selective COX-1 inhibitor
SC-560 was ineffective (Figure 4C). PGE₂ levels in whole
retina were reduced by 65% 24 hours after APHS treatment.
Moreover, intravitreal injection of PGE₂ after the hyperoxic
period led to a significant (albeit mild) increase in intravitreal
neovascularization.

To confirm the role of COX-2 in retinal neovasculariza-
tion, its involvement was tested using a distinct selective
COX-2 inhibitor, etodolac, as well as a different species, the
rat model of ischemic proliferative retinopathy. Etodolac
carried a marked decrease in retinal neovascularization (stud-
died at 5 days after the first injection) (Figure 5A and 5B). This
effect was reversed by PGE₂.

To further explore the PGE₂ pathway, PGE₂ receptor
expression and its changes during the posthyperoxia period
were studied. Hyperoxia caused a slight decrease in EP₁
(Figure 5C), whereas EP₁ was undetectable (not shown). In
contrast, EP₂ and to a greater extent EP₃ receptor expres-
sion was significantly decreased by hyperoxia and in-
creased substantially during the posthyperoxia period (Fig-
ure 5C), coincidental with COX-2 changes (Figure 2C).
Moreover, addition of the EP₂ agonist butaprost and the
EP₃ agonist M&B28767 reversed in part or exacerbated
the inhibitory effects of etodolac on retinal neovascular-
ization. EP₃ receptor expression also increased in the same
phase in that of the murine eye, predominantly localized in
retinal endothelium (lectin griffonia–positive cells) (Fig-
ure 3f through 3h).
Effects of COX-2 Inhibition and EP3 Stimulation on Expression of Modulators of Angiogenesis

Involvement of COX-2 and EP3 on pro- and antiangiogenic factors, notably VEGF, VEGFR2, TSP-1, and CD36, was studied in retina of models of proliferative retinopathy. Twenty-four hours after removal from hyperoxia, there was an increase in TSP-1 expression. The COX-2 inhibitor etodolac induced a substantial increase in both TSP-1 and CD36, and addition of the EP3 agonist M&B28767 reversed this effect. In contrast, effects of COX-2 on neovascularization could not be explained by the VEGF pathway; VEGF expression, although as anticipated it increased during the posthyperoxic period, was marginally affected by etodolac and M&B28767 (Figure 6A), and VEGFR2 remained unaltered. In accord with in vivo observations, etodolac caused a slight increase in TSP-1 expression in neuroretinovascular endothelial cells, and this effect was reversed by M&B28767 (Figure 6B), consistent with EP3 expression on retinal endothelium (Figure 3f).

Discussion

Inflammatory mediators contribute to the pathogenesis of ischemic proliferative retinopathy. In a related manner, COX-2 has been implicated in angiogenesis, especially of tumors. Although COX inhibition diminishes retinal neovascularization in ischemic models, the specific involvement of COX-2 and the identity of its products in this process have not been elucidated. Our findings disclose an important role for this immediate-early gene product in proliferative retinopathy. COX-2 expression increased coincidentally with that of EP2 and EP3 during the ischemic (posthyperoxic in models) phase associated with proliferation, particularly localized, respectively, in astrocytes and in endothelial cells of the NFL. COX-2 contributed to the preretinal neovascularization in different models of ischemic retinopathies, which seems to be mediated by PGE2 acting via EP2 and to a greater extent EP3 receptors, and these in turn modulate the antiangiogenic factor TSP-1 and its receptor CD36 on target endothelial cells.

COX-2 was abundantly present in synaptic regions of the retina of all species studied (human, mouse, and rat) as seen in the brain. In addition, COX-2 was induced in the NFL of retinas of humans with diabetes and vascular obstruction (case 12) and in animals after hyperoxia, hence during hypoxic-ischemic phases; in these instances, COX-2 was mostly induced in astrocytes (but also in endothelium) [Figure 5].
dominant generator of PGE2 under certain inflammatory conditions, whereas COX-1 inhibition was ineffective. Moreover, administration of the well-recognized proangiogenic COX product PGE2,5,10 (Figure 4) reversed the antiangiogenic effects of COX-2 inhibitors in the retina (Figures 4 and 5). In view of the significant COX-1 expression even during the hypoxic phase (Figure 2C and 2D), one would have predicted some effect of COX-1 inhibition on neovascularization. However, COX-2 seems to be coregulated and biochemically coupled with the inducible gene product microsomal PGE2 synthase, a dominant generator of PGE2 under certain inflammatory conditions,30 whereas COX-1 appears to be mostly coupled to the constitutive cytosolic PGE2 synthase. This inference may explain at least in part the differences observed between COX-1 and COX-2 inhibitors. Of note, we found augmented microsomal PGE2 synthase during the posthyperoxic period (data not shown) and, accordingly, a major role for COX-2 in PGE2 generation during hypoxia (Figure 2E).

The angiogenic effect of PGE2 seemed to be mediated via its EP2 and especially EP3 receptors, as specific stimulation of these receptors reversed the effects of etodolac on neovascularization (Figure 5); selective antagonists to these receptors are not readily available. Of interest, EP2 and EP3 have recently been reported to participate in colorectal tumor angiogenesis,31,32 and these effects may be mediated via VEGF, a major factor in ischemic proliferative retinopathy.26,27 Similarly, COX-2 inhibition downregulated VEGF in colon tumor endothelial cells.8 But in other endothelial cells (breast tumor and cornea), COX-2 inhibition affected the basic fibroblast growth factor pathway,9 which plays a minor role in ischemic proliferative retinopathy.33 Endothelial cells are not homogeneous throughout tissues, and in retina the effect of COX-2 inhibition was largely unrelated to the VEGF pathway (Figure 6). Thus, COX-2 inhibition may interfere with pathways that are independent of specific growth factors. Plausible candidate pathways are through TSP-1 and its receptor CD36, which inhibit angiogenesis via p38 mitogen-activated protein kinase and caspase 3,34 This conjecture is supported by an upregulation of TSP-1 and CD36 by COX-2 inhibitor and reversal of these effects by EP3 stimulation (Figure 6). Although a prostaglandin D2 metabolite–dependent peroxisome proliferator-activated receptor-γ-mediated induction of TSP-1 and CD36 has been documented,35 an EP3-evoked one as we observed (Figure 6) discloses a previously undescribed mode of regulation of these angiogenic factors.

In summary, COX-2 contributes markedly to preretinal neovascularization in ischemic retinopathies, and this effect seems to be PGE2 mediated mostly via EP3 receptors implicating a new interaction through TSP-1 and CD36. Results suggest that selective COX-2 inhibitors could be used for the control of pathological vitreal neovascularization in ischemic proliferative retinopathy. More specifically, EP3 (and possibly EP2) antagonists may be more selective by sparing the potentially physiologically desirable effects of the various COX-2 products.

Acknowledgments
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