Ocular-specific ER stress reduction rescues glaucoma in murine glucocorticoid-induced glaucoma

Gulab S. Zode, Arti B. Sharma, Xiaolei Lin, Charles C. Searby, Kevin Bugge, Gun Hee Kim, Abbot F. Clark, and Val C. Sheffield

1Department of Pediatrics and 2Howard Hughes Medical Institute, University of Iowa, Iowa City, Iowa, USA.
3Department of Cell Biology and Immunology and North Texas Eye Research Institute, University of North Texas Health Science Center at Fort Worth, Fort Worth, Texas, USA.

Administration of glucocorticoids induces ocular hypertension in some patients. If untreated, these patients can develop a secondary glaucoma that resembles primary open-angle glaucoma (POAG). The underlying pathology of glucocorticoid-induced glaucoma is not fully understood, due in part to lack of an appropriate animal model. Here, we developed a murine model of glucocorticoid-induced glaucoma that exhibits glaucoma features that are observed in patients. Treatment of WT mice with topical ocular 0.1% dexamethasone led to elevation of intraocular pressure (IOP), functional and structural loss of retinal ganglion cells, and axonal degeneration, resembling glucocorticoid-induced glaucoma in human patients. Furthermore, dexamethasone-induced ocular hypertension was associated with chronic ER stress of the trabecular meshwork (TM). Similar to patients, withdrawal of dexamethasone treatment reduced elevated IOP and ER stress in this animal model. Dexamethasone induced the transcriptional factor CHOP, a marker for chronic ER stress, in the anterior segment tissues, and CHOP deletion reduced ER stress in these tissues and prevented dexamethasone-induced ocular hypertension. Furthermore, reduction of ER stress in the TM with sodium 4-phenylbutyrate prevented dexamethasone-induced ocular hypertension in WT mice. Our data indicate that ER stress contributes to glucocorticoid-induced ocular hypertension and suggest that reducing ER stress has potential as a therapeutic strategy for treating glucocorticoid-induced glaucoma.

The ER is involved in the synthesis and processing of secreted and membrane proteins. Properly folded proteins are transported to the Golgi network, whereas misfolded proteins are retained in the ER. When ER stress becomes chronic and is not resolved, ER stress can lead to activation of cell death via induction of CHOP, ER-specific caspase 12, and several other factors (24, 25). The UPR is a cytoprotective response to ER stress. However, failure of the UPR to resolve ER stress plays an important role in several human diseases (20). Recently, we demonstrated that chronic ER stress is associated with TM dysfunction and development of glaucoma in a mouse model of POAG (26, 27). We have also shown that expression of mutant myocilin (MYOC) induces ER stress in the TM, which is associated with elevation of IOP in Tg-MYOC<sup>2437H</sup> mice. In the present study, we sought to examine whether increased ER stress in the TM is responsible for elevating IOP in other models of glaucoma. We particularly chose to examine glucocorticoid-induced glaucoma because, similar to...
POAG, glucocorticoid-induced ocular hypertension is also caused by increased aqueous humor outflow resistance. Dexamethasone treatment has previously been shown to induce ultrastructural changes in the TM, including the proliferation and activation of the ER and the Golgi apparatus, as well as increased deposition of ECM proteins (17, 28–30). Glucocorticoids are also known to cause increased secretory load in the TM, which can induce ER stress, since it overwhelms the ER quality control system (22).

Prednisolone, a synthetic glucocorticoid, has been shown to induce ER stress and activate the UPR in insulin-secreting INS-1E cells (31). Therefore, we hypothesize that glucocorticoids induce ER stress in the TM, which is associated with IOP elevation in glucocorticoid-induced glaucoma.

The objectives of the present study were to develop a murine model of steroid-induced glaucoma and to use this model to investigate the role of ER stress in glucocorticoid-induced ocular hypertension.

Figure 1
Topical ocular dexamethasone induces glaucoma in mice. (A) Elevated IOP in dexamethasone-treated C57BL/6 mice. Topical ocular vehicle (sterile PBS) or dexamethasone (0.1%) was administered 3 times daily for up to 20 weeks. IOP measurements of dexamethasone-treated (n = 20–24) and vehicle-treated (n = 20) mice are shown from week 0 to 6 of treatment. **P < 0.005, ***P < 0.0001, unpaired t test. (B) Progressive RGC functional loss in dexamethasone-treated mice. PERG amplitudes (P50-N95) in vehicle and dexamethasone-treated mice at 5 (n = 5), 15 (n = 10), and 20 (n = 6) weeks of treatment. (C and D) Loss of RGCs in dexamethasone-treated mice. (C) Representative images of Nissl-stained whole-mount retinas from mice treated for 20 weeks with vehicle or dexamethasone. (D) Remaining cells in ganglion layer were counted in the periphery of the retina. n = 5 (vehicle); 10 (dexamethasone). **P = 0.0045, unpaired t test. (E and F) Progressive optic nerve degeneration in mice treated with dexamethasone for 10 or 15 weeks. Optic nerve sections were stained with PPD (E), and mean axon counts (F) were compared in dexamethasone- (n = 8) and vehicle-treated (n = 7–10) mice. *P = 0.0174, **P = 0.0013 vs. vehicle, unpaired t test. Scale bar: 10 μm.
Topical ocular dexamethasone increases MYOC and actin levels in the TM.

**Optic nerve degeneration.** We also examined optic nerve axonal degeneration by staining optic nerve cross-sections with paraphenylenediamine (PPD) and quantified optic nerve axons. Optic nerve degeneration was evident after dexamethasone treatment (Figure 1E). Dexamethasone-treated mice lost 15% of axons compared with vehicle-treated mice by 10 weeks of treatment, and 29% by 15 weeks (Figure 1F), suggestive of progressive neuronal degeneration. We also found that optic nerve area of dexamethasone-treated mice was significantly reduced compared with vehicle-treated mice (reduced 15% by 10 weeks and 30% by 15 weeks; Supplemental Figure 5).

Topical dexamethasone increases MYOC, actin, and ECM proteins in the TM

A hallmark of dexamethasone treatment of the TM is induction of MYOC, actin, and ECM proteins, including fibronectin (FN) (14, 33–36). We next investigated whether topical ocular dexamethasone increases these known biochemical changes in the TM in our mouse model. We performed immunostaining for MYOC and actin on mice treated with vehicle or dexamethasone for 3 weeks (Figure 2). Immunostaining for MYOC revealed a prominent increase in MYOC labeling in the TM of dexamethasone-treated eyes compared with vehicle-treated mice. We also observed a slight increase in MYOC staining in the CB of dexamethasone-treated eyes. Similarly, phalloidin, which stains F-actin, revealed a prominent increase in actin in the TM and CB of dexamethasone-treated mice. We also examined whether dexamethasone increases FN. Western blot analysis of the anterior segment tissues from vehicle- and dexamethasone-treated mice showed increased levels of FN with dexamethasone treatment (Supplemental Figure 6).
Topical ocular dexamethasone induces ER stress and activates the UPR in mouse TM in vivo

We next sought to examine whether dexamethasone-induced ocular hypertension is associated with induction of ER stress in the anterior segment tissues. Topical dexamethasone treatment did not elevate IOP in WT mice at 1 week of treatment (vehicle, 16.1 ± 0.26 mmHg; dexamethasone, 15.9 ± 0.14 mmHg; n = 5 per group). Western blot analysis of the anterior segment tissues obtained from these mice demonstrated that 1 week of dexamethasone treatment increased ER stress and activated the UPR, as evidenced by increased levels of GRP78, ATF-4, cleaved ATF-6, CHOP, and spliced XBP-1 proteins in these tissues (Figure 4A). Dexamethasone also increased MYOC levels in the anterior segment tissues, consistent with previous reports (35).

These data indicated that topical dexamethasone induces ER stress in WT mice prior to IOP elevation. Dexamethasone also increased GRP78 and CHOP proteins in anterior segment tissues after 8 weeks of treatment (Supplemental Figure 7), indicative of the presence of chronic ER stress. In addition, a prominent increase in GRP78 labeling was detected in the TM of mice treated for 8 weeks with dexamethasone compared with vehicle treatment (Figure 4B). Although a weak signal for GRP78 was detected in the corneal endothelium in vehicle-treated mice, corneal GRP78 did not appear to change in dexamethasone-treated mice. In addition, GRP78 was abundantly present in CB, and its level remained unchanged in dexamethasone-versus vehicle-treated mice (Figure 4B).

Withdrawal of dexamethasone leads to reduction of elevated IOP and ER stress—associated with dexamethasone treatment

In humans, withdrawal of glucocorticoid in most cases returns elevated IOP to baseline (18, 38). Therefore, we examined whether a similar phenomenon occurred in our mouse model. Topical dexamethasone or vehicle eye drops were given to WT mice for 3 weeks. Dexamethasone significantly elevated IOP at 3 weeks of treatment (dexamethasone, 22.5 ± 0.67 mmHg; vehicle, 17.3 ± 0.67 mmHg; n = 10; P < 0.0001, t test). After 3 weeks of treatment, dexamethasone-treated mice were randomly divided into 2 groups: one received topical dexamethasone, and the other vehicle (i.e., dexamethasone withdrawal), for another 2 weeks. Subsequent IOP measurements were taken at 1 week after withdrawal (vehicle, 17.5 ± 0.68 mmHg; dexamethasone, 17.3 ± 0.7 mmHg; n = 5 per group).

Figure 4

Topical dexamethasone induces ER stress and activates the UPR in TM tissues of WT mice. (A) GRP78, activated ATF-6α, ATF-4, spliced XBP-1, CHOP, MYOC, and GAPDH (loading control) were examined by Western blot analysis in anterior segment tissues of mice treated for 1 week with vehicle or dexamethasone (n = 4 per group). (B) Representative immunostaining for GRP78 in the anterior segment tissues of mice treated for 8 weeks with vehicle or dexamethasone (n = 5 per group), showing increased GRP78 in the TM (arrows) of dexamethasone-treated mice. CE, corneal endothelium. Scale bars: 50 μm.
revealed that dexamethasone-withdrawn mice had significantly reduced IOP compared with continued dexamethasone treatment, with levels returning to baseline (Figure 5A). These data indicated that withdrawal of dexamethasone reduces dexamethasone-induced ocular hypertension, similar to the response seen in human patients.

We next examined whether withdrawal of dexamethasone treatment also decreases ER stress. Western blot analysis of anterior segment tissues demonstrated that dexamethasone significantly increased GRP78. However, GRP78 levels were significantly reduced to baseline in dexamethasone-withdrawn mice (Figure 5, B and C). Interestingly, MYOC and FN levels were also reduced after dexamethasone withdrawal (Figure 5, D and E).

**Deletion of Chop protects from dexamethasone-induced ocular hypertension**

Induction of CHOP has been shown to be associated with chronic ER stress. In our model, we observed that dexamethasone treatment increased CHOP levels in the anterior segment tissues, preceding IOP elevation by 1 week (Figure 4A). CHOP levels were also increased at 8 weeks of treatment (Supplemental Figure 7). Deletion of Chop has been shown to be protective against chronic ER stress in multiple studies (25, 39, 40). Thus, we examined whether deletion of Chop also protects against dexamethasone-induced ocular hypertension. Topical ocular dexamethasone was given to WT and Chop knockout mice (C57BL/6 background) for 3 weeks, and IOP was measured every week. Topical ocular dexamethasone significantly elevated IOP in WT mice after 3 weeks of treatment (dexamethasone, 23.2 ± 0.6 mmHg; vehicle, 15.8 ± 0.8 mmHg; Figure 6A). However, IOP was not significantly elevated with dexamethasone compared with vehicle treatment in Chop knockout mice (dexamethasone, 18.2 ± 0.8 mmHg; vehicle, 15.7 ± 0.6 mmHg; Figure 6A).

We further examined ER stress markers in the anterior segment tissues of WT and Chop knockout mice. In WT mice, dexamethasone induced ER stress markers, including GRP78 and CHOP along with MYOC (Figure 6B). However, dexamethasone treatment reduced GRP78, ATF-4, and MYOC levels compared with vehicle treatment in Chop knockout mice (Figure 6C). Densitometric analysis revealed that dexamethasone increased GRP78 and MYOC levels 2.5-fold compared with vehicle control in WT mice (Figure 6D). However, dexamethasone-treated Chop knockout mice exhibited significantly decreased GRP78 and MYOC levels compared with dexamethasone-treated WT mice. These data demonstrated that deletion of Chop protects mice from dexamethasone-induced ocular hypertension and also reduces ER stress associated with dexamethasone treatment.

**Reduction of ER stress by the chemical chaperone sodium 4-phenylbutyrate (PBA) prevents IOP elevation by dexamethasone**

We next sought to examine whether reducing ER stress would rescue dexamethasone-induced ocular hypertension. WT mice were given topical ocular vehicle or dexamethasone for 3 weeks. Dexamethasone-treated mice were divided into 2 groups: one received topical dexamethasone, and the other vehicle (i.e., dexamethasone withdrawal), for another 2 weeks. (A) 2 weeks of dexamethasone withdrawal significantly reduced IOP (n = 10 per group). P values were determined by 1-way ANOVA. (B) Western blot analysis of GRP78, MYOC, and FN in anterior segment tissue lysates. (C–E) Densitometric analysis of GRP78 (C), MYOC (D), and FN (E) levels, normalized to loading control GAPDH, revealed that dexamethasone withdrawal reduced the dexamethasone-associated elevations in these proteins. *P < 0.05, **P < 0.005, 1-way ANOVA.

**Figure 5**

Dexamethasone withdrawal reduces dexamethasone-associated elevations in IOP and ER stress. WT mice were given topical ocular vehicle or dexamethasone for 3 weeks (IOP measurements confirmed elevated IOP with dexamethasone treatment). At this time point, dexamethasone-treated mice were randomly divided into 2 groups: one received topical dexamethasone, and the other vehicle (i.e., dexamethasone withdrawal), for another 2 weeks. (A) 2 weeks of dexamethasone withdrawal significantly reduced IOP (n = 10 per group). P values were determined by 1-way ANOVA. (B) Western blot analysis of GRP78, MYOC, and FN in anterior segment tissue lysates. (C–E) Densitometric analysis of GRP78 (C), MYOC (D), and FN (E) levels, normalized to loading control GAPDH, revealed that dexamethasone withdrawal reduced the dexamethasone-associated elevations in these proteins. *P < 0.05, **P < 0.005, 1-way ANOVA.
elevated IOP compared with topical ocular vehicle treatment (dexamethasone, 22.6 ± 0.5 mmHg; vehicle, 16 ± 0.7 mmHg; Figure 7A). Interestingly, when PBA was given to dexamethasone-treated mice, IOP was significantly reduced compared with mice treated with dexamethasone alone (dexamethasone plus PBA, 18.9 ± 0.5 mmHg; dexamethasone, 22.6 ± 0.5 mmHg; Figure 7A). These data demonstrated that systemic PBA prevents IOP elevation by dexamethasone.

We next examined whether PBA reduces ER stress induced by dexamethasone treatment. Western blot and densitometric analyses of ER stress markers in the anterior segment tissues demonstrated that a 3-week treatment with dexamethasone increased levels of the ER stress markers GRP78, spliced XBP-1, and CHOP, which were significantly reduced by PBA treatment (Figure 7, B and C). Interestingly, PBA treatment also decreased the elevated FN levels associated with dexamethasone treatment (Supplemental Figure 8). We further examined the effect of PBA on dexamethasone-induced ER stress using primary human TM cells. TM cells were treated with dexamethasone with or without PBA (5 mM) for 48 hours. Western blot analysis of cell lysates demonstrated that dexamethasone treatment alone increased levels of GRP78, GRP94, MYOC, and phosphorylated eIF2α in TM cells (Figure 7D). Expression of all these ER stress markers was reduced in TM cells with concomitant PBA treatment. These data demonstrated that PBA prevents dexamethasone-induced ocular hypertension and reduces ER stress associated with dexamethasone treatment in the anterior segment tissues.

Discussion

Ocular hypertension is a serious side effect of glucocorticoid therapy that can lead to a secondary iatrogenic form of open-angle glaucoma and, if unrecognized, subsequent vision loss. In the present study, we developed a new mouse model of glucocorticoid-induced glaucoma and investigated the molecular mechanisms that lead to ocular hypertension. Topical ocular dexamethasone treatment induced ocular hypertension and resulted in open-angle glaucoma in otherwise healthy C57BL/6 mice that was similar to steroid glaucoma in human patients. We further demonstrated that dexamethasone induced ER stress in the TM, which was associated with IOP elevation. Withdrawal of dexamethasone treatment reduced dexamethasone-induced elevations in IOP and ER stress. Dexamethasone also induced expression of CHOP, a marker of chronic ER stress, in anterior segment tissues. Deletion of Chop reduced ER stress in the TM and, in turn, protected against glucocorticoid-induced ocular hypertension. Reduction of ER stress by PBA prevented dexamethasone-induced IOP elevation, which further supports the involvement of ER stress in glucocorticoid-induced ocular hypertension. Thus, chronic ER stress appears to play a central role in the development of ocular hypertension in our mouse model of glucocorticoid-induced glaucoma.

Glucocorticoid-induced ocular hypertension has been studied in several animal models, including monkeys (41), cows (42), cats (43), rabbits (44), sheep (45), rats (46), and recently mice (47). However, a model of glucocorticoid-induced glaucoma has not previously been developed. A recent study by Whitlock and colleagues demonstrated that systemic dexamethasone administration elevated IOP by 3–4 mmHg in hybrid mice (47). In our present study, topical ocular dexamethasone elevated the IOP of normal C57BL/6J mice by 7 mmHg. In addition to developing ocular hypertension, chronic dexamethasone treatment caused RGC structural and functional loss, as well as optic nerve degeneration, similar to that observed in patients with glucocorticoid-induced glaucoma. In our model, as in the human disorder, elevated IOP preceded PERG abnormalities: examination of RGC function by PERG at 5 weeks (2–3 weeks after elevated IOP) showed a nonsignificant reduction in PERG amplitudes in dexamethasone-treated mice. Thus, it is unlikely that dexamethasone leads to RGC loss within 2–3 weeks prior to IOP elevation in our mouse model. Withdrawal of dexamethasone treatment normalized mouse IOP to baseline levels, similar to human patients. Consistent with previously reported studies, dexamethasone-induced similar biochemical changes in the TM in our mouse model of glucocorticoid-induced glaucoma, including increased...
MYOC, actin, and FN. These data indicated that our mouse model appropriately mimics human glucocorticoid-induced glaucoma.

Glucocorticoids induce ocular hypertension in a subset of the human population (10, 12). Differential glucocorticoid responsiveness is also observed in several animal models, including non-human primate eyes (41), rabbits (44), mice (47), and the bovine perfusion cultured anterior segment model (48). In contrast, a 100% responder rate was reported in cattle in vivo (42). Whitlock and colleagues systemically administered dexamethasone to hybrid mice (B6:129) and showed increased IOP in approximately one-half of the mice (47). In our present study, 90%–95% of mice treated with dexamethasone developed ocular hypertension after 5 weeks of treatment in our genetically homogeneous pure C57BL/6 strain. These findings suggest that genetic heterogeneity may be responsible for the differential glucocorticoid responsiveness. Several studies have suggested that differences in the levels of alternatively spliced glucocorticoid receptor isoforms regulate glucocorticoid responsiveness in TM cells (37, 49).

Our data demonstrated that induction of ER stress in the TM was associated with dexamethasone-induced ocular hypertension.

Specifically, ER stress induction preceded IOP elevation. ER stress was also chronically elevated over the course of treatment. Cessation of dexamethasone treatment returned elevated IOP to baseline and also decreased ER stress associated with dexamethasone treatment in anterior segment tissues. Furthermore, knockout of Chop or treatment with PBA protected mice from dexamethasone-induced ocular hypertension, along with reducing ER stress in the anterior segment. It is not entirely clear how dexamethasone induces ER stress in the TM. Dexamethasone is known to increase the overall protein secretory load, which can lead to ER stress. In our model, dexamethasone increased MYOC, FN, and actin in primary TM cells as well as in the mouse TM. We hypothesize that increased protein processing and accumulation of these proteins in the TM may result in ER stress in our model of glucocorticoid-induced ocular hypertension. Consistent with this hypothesis, our results showed that increased levels of MYOC, actin, and FN were associated with dexamethasone-induced ocular hypertension. Specifically, withdrawal of dexamethasone treatment decreased MYOC and FN levels in the anterior segment. In addition, Chop knockout mice were protected from dexamethasone-induced IOP elevation and also had reduced levels of MYOC.

Figure 7
Decreasing ER stress by administration of the chemical chaperone PBA reduces IOP elevation by dexamethasone. (A–C) WT mice were given topical ocular vehicle or dexamethasone for 3 weeks. Dexamethasone-treated mice were divided into 2 groups: one received water, the other received 20 mM PBA in drinking water. (A) PBA treatment significantly protected from dexamethasone-induced IOP elevation (n = 20 per group). ***P < 0.05, **P < 0.005, 1-way ANOVA. (B and C) Western blot (B) and densitometric analysis (C) of ER stress markers in anterior segment tissues revealed that combined dexamethasone and PBA treatment reduced ER stress markers compared with dexamethasone treatment alone (n = 5 per group). (D) PBA reduced ER stress associated with dexamethasone in human TM cells. Human TM cells were treated with dexamethasone with or without 5 mM PBA. Total cell lysates were subjected to Western blot analysis for GRP78, GRP94, phosphorylated and total eIF2α, MYOC, and GAPDH.
and markers of ER stress in the anterior segment tissues. Furthermore, treatment with the chemical chaperone PBA reduced elevated IOP and decreased FN, MYOC, and ER stress in the TM. Together, these findings suggest that induction of ER stress associated with increased levels of MYOC and ECM proteins may cause dysfunction of the TM, resulting in IOP elevation in glucocorticoid-induced glaucoma. Our present findings provide new directions for understanding glucocorticoid-induced ocular hypertension.

This study demonstrated a prominent increase in GRP78, MYOC, and actin levels in the TM. It is widely accepted that biochemical and morphological changes in the TM are responsible for increased TM outflow resistance and ocular hypertension in steroid-induced glaucoma (14). Consistent with this, Kumar et al. recently described a new model of steroid-induced changes in mouse outflow facility and demonstrated that steroid treatment reduces outflow facility, despite no noticeable change in IOP (50). In addition to our findings in the TM, we observed increased immunostaining for MYOC and actin in the CB of dexamethasone-treated WT mice; thus, we cannot exclude a potential role for the CB in ocular hypertension.

Several studies have shown that induction of Chop is associated with cellular dysfunction and that its overexpression leads to ER stress–mediated cell death (25). We observed that dexamethasone induced Chop over the course of treatment. Interestingly, deletion of Chop protected mice from dexamethasone-induced ocular hypertension and also reduced ER stress compared with WT mice. CHOP may theoretically cause TM dysfunction and/or TM cell death, thus resulting in IOP elevation. TUNEL staining of the anterior chamber did not show apoptotic TM cell death (Supplemental Figure 9), suggestive of a nonapoptotic role of Chop in our mouse model of steroid glaucoma. Deletion of Chop has previously been shown to protect against ER stress by decreasing ER client protein load and changing redox conditions (51). Deletion of Chop improves β cell function and protects from ER stress by enhancing UPR and oxidative stress response genes (39). Chop deletion may also prevent glucocorticoid-induced dysfunction of the TM and prevent ocular hypertension by acting upstream of the ER stress pathway. It is also possible that Chop deletion enhances ER function in handling misfolded proteins and overall secretory pathway function, thereby protecting TM cells from the consequences of protein misfolding. Consistent with this hypothesis, we observed reduced levels of MYOC and ER stress in dexamethasone-treated Chop knockout mice compared with vehicle-treated Chop knockout and dexamethasone-treated WT mice. Similarly, PBA treatment reduced dexamethasone-induced MYOC and FN levels, which in turn decreased ER stress and prevented IOP elevation. Alternatively, Chop deletion may inhibit the progression of stressed TM cells to apoptosis and activate a positive feedback mechanism that decreases ER stress directly in TM tissues.

Steroid responsiveness is higher in POAG patients and their descendants. However, steroid responsiveness in MYOC patients has not been studied. Because glucocorticoids induce WT MYOC expression, it was originally hypothesized that increased MYOC accumulates in the TM, leading to increased outflow resistance and IOP elevation in glucocorticoid glaucoma. However, transgenic mice overexpressing WT MYOC do not develop glaucoma, which suggests that overexpression of MYOC is not in itself sufficient to cause glaucoma in mice (52). It is possible that dexamethasone alters WT MYOC processing in the ER, thus reducing its secretion and inducing ER stress in the TM. Since induction of ER stress is associated with elevation of IOP in Tg-MYOC14771 mice, which express mutant MYOC, it is conceivable that dexamethasone treatment may worsen the glaucoma phenotypes of Tg-MYOC14771 mice. Specifically, dexamethasone increases WT MYOC, which can interact with mutant MYOC (53). These events can lead to increased MYOC aggregates in the ER of the TM, thus worsening the glaucoma in Tg-MYOC14771 mice. Future studies will be aimed at understanding the role of WT and mutant MYOC in glucocorticoid-associated glaucoma.

Systemic PBA treatment prevented glucocorticoid-induced IOP elevation by reducing ER stress in the anterior segment. Previously, we demonstrated that topical PBA rescued glaucoma in Tg-MYOC14771 mice by reducing mutant MYOC accumulation and facilitating MYOC secretion in the aqueous humor, consequently reducing ER stress in the TM (26, 27). Thus, it is conceivable that PBA may prevent ER stress and IOP elevation in glucocorticoid-induced ocular hypertension by similar mechanisms, including decreasing ER load, enhancing protein secretion, and reducing protein accumulation in the TM. Consistent with this hypothesis, dexamethasone-induced MYOC and FN levels were significantly decreased to baseline levels by PBA treatment. It is unlikely that PBA has a direct effect on MYOC transcript levels, since PBA has been shown to increase MYOC secretion within 30 minutes of treatment (54), suggestive of a direct effect of PBA on the secretory pathway.

In conclusion, we here established a mouse model of glucocorticoid-induced glaucoma and demonstrated that ER stress played a critical role in glucocorticoid-induced ocular hypertension. Furthermore, our demonstration of reduced ER stress by chemical chaperones such as PBA provides a promising potential treatment for glaucoma. These studies provide new mechanistic insights into glucocorticoid-induced ocular hypertension and a novel target for treatment of glucocorticoid-induced glaucoma.

Methods

Mouse buisandry. C57BL/6j mice were obtained from the Jackson Laboratory. Mice were housed and bred at the University of Iowa as described previously (26).

Topical ocular dexamethasone and vehicle treatment. 4 independent experiments containing at least 10 mice per group were performed to evaluate the effect of topical ocular dexamethasone administration. Topical 0.1% dexamethasone phosphate (Bausch & Lomb Inc.) was used. Sterile PBS was used as a vehicle eye drop. 3-month-old C57BL/6j mice were given topical ocular 0.1% dexamethasone phosphate or sterile PBS (vehicle) eye drops 3 times daily for up to 20 weeks. A small eye drop (~20 μl) was applied to both eyes. The initial daily dose was given between 9 am and 10 am, the second dose between 1 pm and 2 pm, and the third dose between 6 pm and 7 pm. To ensure the effective penetration of the eye drops into the anterior chamber, mice were lightly held for 30–40 seconds after drop administration, then released in their cages. Chop knockout mice (Jackson Labs) were obtained from the laboratory of T. Rutkowski (University of Iowa). For dexamethasone withdrawal, WT mice were given topical vehicle or dexamethasone for 3 weeks. At 3 weeks, the dexamethasone-treated mice were randomly divided into 2 groups: one received topical dexamethasone, and the other vehicle, for another 2 weeks. IOP was measured during this period, and anterior segment tissues were isolated for Western blot analysis of ER stress.

IOP measurements. IOP was measured with a rebound tonometer, as previously described (26). In brief, mice were acclimated to the procedure room and anesthetized with 2.5% isoflurane plus 100% oxygen. IOP was measured with a tonometer (TonoLab; Colonial Medical Supply). All IOP cohorts included male and female mice. Daytime IOP was measured between 10 am and 2 pm. IOP was measured every week for several weeks in each group of mice. Mice were anesthetized with isoflurane for very short times (approximately 2 minutes); longer isoflurane exposure rapidly
decreased IOP, especially in dexamethasone-treated mice. IOP measurements were performed in a masked manner by a technician uninformed of treatment group. Because each eye responds differently to treatment, we considered each eye measurement as an independent sample.

PERG. PERG was used to objectively measure the function of RGCs by recording amplitudes and latency of N35-P50 and P50-N95 PERG waveforms, as described previously (26).

Retina staining. Nissl staining of retinal whole mounts was used to determine the number of cells within the RGC layer, as described previously (37). Briefly, TM cells were grown in DMEM containing 5% fetal bovine serum (FBS) and 1% Penicillin-Streptomycin (P/S) in 35 mm dishes at 37°C. After 3 days, the medium was changed to fresh DMEM containing 3% FBS and 1% P/S. When the cells reached a confluency of 80%, the medium was changed to fresh DMEM containing 0% FBS and 1% P/S. The cells were incubated for 48 hours, and then fixed with 4% paraformaldehyde for 10 minutes. The cells were washed with PBS three times and then permeabilized with 0.1% Triton X-100 for 5 minutes. The cells were then incubated with primary antibodies overnight at 4°C. The primary antibodies used for immunostaining were obtained from Santa Cruz Biotechnology Inc. Antibody for GRP78 was obtained from GeneTex (catalog no. GTX63722). Total IRE1α were purchased from Santa Cruz Biotechnology Inc. Antibody for ATF-6 was obtained from Imagenex Corp. GRP78, MYOC (catalog no. sc137233), and spliced XBP-1 antibodies were purchased from Santa Cruz Biotechnology Inc. Phosphorylated IRE1α antibody was obtained from GeneTex (catalog no. GTX63722). Total IRE1α antibody was obtained from Santa Cruz Biotechnology Inc.

Statistical analysis. All data are presented as mean ± SEM. For comparisons between 2 groups, unpaired 1-tailed Student’s t-test was used. For comparisons among 3 or more groups, 1-way ANOVA with Bonferroni multiple-comparison test was used. A P-value less than 0.05 was considered significant.

Immunostaining. Mouse anterior segments were fixed in 4% paraformaldehyde and embedded in OCT. Sections were then blocked with 5% normal serum. Slides were incubated overnight with primary antibody (1:250) and washed 3 times with PBS, followed by a 2-hour incubation with appropriate Alexa Fluor secondary antibodies (1:200; Invitrogen). Sections were subsequently incubated with DAPI for 30 minutes to stain nuclei, washed, and then mounted. Images were captured using a Zeiss 710 confocal imaging system. The MYOC antibody used for immunostaining was obtained from S. Tomarev (NIH). GRP78 was obtained from GeneTex (1:250). Donkey anti-goat (1:500) and phallolidin stain (1:100) were obtained from Invitrogen.

Western blot analysis. Anterior segment tissues may change protein levels in each sample. However, it should be noted that total cumulative response shown by densitometric analysis more accurately demonstrates the overall pattern of response. Considering the small size of anterior segment tissues, total protein lysates from each eye only allowed a few Western blot analyses. Therefore, we focused on analysis of the selected ER stress markers GRP78, ATF-4, and CHOP in most subsequent studies. We established induction of ER stress by dexamethasone in Figures 3 and 4 using several ER stress markers, including phosphorylation of IRE1α and eukaryotic translation initiation factor 2α (eIF2α) and increased levels of GRP78, GRP94, cleaved ATF-6, ATF-4, and CHOP. To ensure equal protein loading, the same blot was subsequently incubated with a GAPDH monoclonal antibody (Cell Signalling Technology Inc.). Quantitation was done using Image J software. Antibodies for GRP94, phosphorylated and total eIF2α, and CHOP were purchased from Cell Signalling Technology Inc. Antibody for ATF-4 was purchased from Imagenex Corp. GRP78, MYOC (catalog no. sc137233), and spliced XBP-1 antibodies were purchased from Santa Cruz Biotechnology Inc. Phosphorylated IRE1α antibody was obtained from GeneTex (catalog no. GTX63722). Total IRE1α antibody was obtained from Santa Cruz Biotechnology Inc.

Acknowledgments
This work was supported by funding from the National Eye Institute (grants R01 EY10564 to V.C. Sheffield, K99 EY022077 to G.S. Zode, and 2R01EY016242 to A.F. Clark). V.C. Sheffield is investigator of the Howard Hughes Medical Institute. The authors acknowledge Alcon Labs and the Knights Templar Eye Foundation for providing financial assistance for some experiments. The authors thank Joseph Conner Peter and Allen Choi for assistance in some experiments, Adam Hedberg for technical help with slit-lamp analysis, and Matthew Harper for help with PERG.

Received for publication October 7, 2013, and accepted in revised form January 30, 2014.
Biological and Immunological and North Texas Eye Research Institute, University of North Texas Health Science Center at Fort Worth, 3500 Camp Bowie Blvd., Fort Worth, Texas 76107, USA. Phone: 817.735.0360; Fax: 817.735.2637; E-mail: gulab.zode@untbhc.edu.

Gulab S. Zode’s present address is: Department of Cell Biology and Immunology and North Texas Eye Research Institute, University of North Texas Health Science Center at Fort Worth, Texas, USA.