AAV-Mediated Gene Therapy for Retinal Degeneration in the *rd10* Mouse Containing a Recessive PDE*β* Mutation

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Abstract

Purpose—To test AAV-mediated gene therapy in the *rd10* mouse, a natural model of recessive RP caused by mutation of the *β*-subunit of rod photoreceptor cGMP phosphodiesterase.

Methods—One eye of a cohort of *rd10* mice kept in a dark environment was subretinally injected at postnatal day (P) 14 with 1 μL AAV5-smCBA-PDE*β*. The contralateral eye was not injected. The animals were then maintained for 2 weeks in the dark before they were moved to a normal 12-hour light/12-hour dark cycling light environment for visually guided behavioral training. Three weeks after injection, treated *rd10* mice were examined by scotopic and photopic electroretinography and then killed for biochemical and morphologic examination.

Results—Substantial scotopic ERG signals were maintained in treated *rd10* eyes, whereas untreated eyes in the same animals showed minimal signals. Treated eyes showed photopic ERG b-wave amplitudes similar to those of the normal eyes; in untreated partner eyes, only half the normal amplitudes remained. Strong PDE*β* expression was observed in photoreceptor outer segments only in treated eyes. Light microscopy showed a substantial preservation of the outer nuclear layer in most parts of the treated retina only. Electron microscopy showed good outer segment preservation only in treated eyes. A visually guided water maze behavioral test under dim light showed significantly improved performance in one eye–treated *rd10* mice compared with untreated mice.

Conclusions—These data demonstrate that P14 administration of AAV5-smCBA-PDE*β* can prevent retinal degeneration in *rd10* mice, as reflected by significant structural, biochemical, electrophysiological, and behavioral preservation/restoration. These results serve as a baseline for studying long-term retinal rescue in *rd10* mice.

Retinal degeneration (RD) is a large family of inherited dystrophies characterized by photoreceptor dysfunction and eventual photoreceptor death. As many as 17 million persons

worldwide have vision loss associated with RD, including patients with retinitis pigmentosa (RP), a disease for which no cure exists. A description of autosomal recessive mutations associated with retinal degeneration dates back to the discovery of the "rodless retina" mouse by Keeler in 1924, which later became known as the *rd1* mouse.[1–3] The *rd1* mouse carries mutations in a gene (*Pde6b*) that encodes the β-subunit of rod photoreceptor cGMP phosphodiesterase (PDEβ).[3,4] The biochemical result is a nonfunctional PDEβ and an accumulation of cGMP.[5] Mutations in the human ortholog of *Pde6b* have been linked to autosomal recessive RP.[6,7] In the *rd1* mouse, photoreceptor degeneration begins at 1 week of age, when photoreceptor outer segments first begin to mature.[8] Rods degenerate first, then cones; the culmination is complete ablation of photoreceptors by about 4 weeks of age.[1,2,8–12] Until recently, the *rd1* mouse was considered one of the best models of human autosomal recessive RP; however, because of the rapid rate of photoreceptor cell loss, providing effective, lasting gene replacement therapy has proven difficult. Subretinal injection of adenoviral, retroviral, or adenoassociated viral vectors encoding the PDEβ gene to neonatal *rd1* mice resulted in partial preservation of photoreceptor structure but little, if any, ERG rescue.[13–16] Because it takes at least 1 week for the viral vector–mediated gene to express in the retina and *PDEβ* is expressed in the retina by postnatal day (P)5 to P6, prenatal gene therapy in *rd1* mice may be considered and has been achieved in mice with the RPE65 form of Leber congenital amaurosis.[17] The course of retinal degeneration in humans, however, though often quicker than the course for other mutations, still takes decades. Thus, questions remain as to why the *rd1* mouse has been relatively unresponsive to standard gene replacement therapy[15] and, in particular, whether any element of recessive mutation in PDEβ makes the resultant retinal degeneration so rapid that the mice are refractory to gene replacement therapy in the mature photoreceptor.

A more recently identified mouse strain that exhibits autosomal recessive retinal degeneration, the *rd10* mouse, has a point mutation in exon 13 of the *Pde6b* gene.[18] Recent natural history studies of the *rd10* mouse indicate that it better emulates the slow progression of typical human autosomal recessive RP than the previously described *rd1* mouse.[19,20] Loss of photoreceptors in the *rd10* mouse begins after 2 weeks of age, with peak photoreceptor death occurring at P25.[20] By 5 weeks most photoreceptor cells have been lost.[19,20] This rate of photoreceptor loss is substantially slower than in the *rd1* animal. Importantly, most photoreceptors in the *rd10* retina are lost after the retina has terminally differentiated, whereas peak photoreceptor cell death in *rd1* occurs before this developmental stage. In addition, it has been found that rearing *rd10* mice in darkness further slows the rate of degeneration by as much as 4 weeks.[19] Taken together, these findings suggest that retinal degeneration in the *rd10* mouse is more analogous to the human condition and perhaps is better suited than the *rd1* mouse for testing PDEβ gene replacement therapy. Recently, studies using stem cell, antiapoptotic, and antioxidant therapies have shown a measure of retinal rescue in *rd10* mice,[21–23] but the potential for gene therapy has not yet been reported.

Adenoassociated virus (AAV)-mediated gene replacement has already proven to be effective for restoring retinal function and for protecting photoreceptor structure in a number of mouse models of retinal disease.[24–26] This approach has been optimized with the use of AAV serotypes that preferentially target photoreceptors in conjunction with ubiquitously expressed constitutive promoters that drive stronger transgene expression than obtained when using cell-specific promoters.[26] The size of the *Pde6b* cDNA (2.6 kb) and the packaging limitation of AAV vectors (4.5 kb, excluding the required terminal DNA sequences) require the use of a relatively small promoter that directs strong and lasting expression. In this study, an AAV serotype 5 vector (AAV5) containing minimal chicken β-actin promoter/CMV enhancer (smCBA) was used to deliver the *Pde6b* gene to the *rd10* mouse retina. The purpose of this gene replacement strategy was to determine whether

retinal degeneration could be delayed in this new murine model of human autosomal recessive PDEβ-based RP, the *rd10* mouse.

Materials and Methods

Animals

C57BL/6J mice and the congenic inbred strain of *rd10* mice were obtained from the Jackson Laboratory (Bar Harbor, ME) and bred at the University of Florida. Except where otherwise indicated, all mice were maintained in the University of Florida Health Science Center Animal Care Services Facilities under a 12-hour light/12-hour dark cycle with less than 15 ft-c environmental illumination. All experiments were approved by the local Institutional Animal Care and Use Committee and were conducted in accordance with the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research and with National Institutes of Health regulations.

Construction of AAV Vectors

AAV5 vectors exhibit higher transduction efficiency in photoreceptors and a faster onset of expression than other AAV serotypes when delivered to the subretinal space (Auricchio A, et al. *IOVS* 2001;42: ARVO Abstract 125)[27] and were, therefore, used for packaging the current vector. Vector plasmids were constructed as previously described.[28] Wild-type murine *Pde6b* cDNA was placed under the control of the ubiquitous, constitutive smCBA promoter[28] to generate pTR-smCBA-PDEβ. Previously, we have shown that the smCBA promoter drives efficient and long-term transgene expression when targeted to photoreceptors through AAV5 (Boye SL, et al. *IOVS* 2006;47:ARVO E-Abstract 852). AAV vectors were packaged and purified according to previously reported methods.[25]

Subretinal Injections

Late-term pregnant *rd10* females were kept in a continuously dark room, except for husbandry at 5 lux or less, and then pups were raised under these same conditions. When the pups were 14 days old, 1 μL AAV5-smCBA-PDEβ (1×10^{10} genome containing vector particles) was subretinally injected into one eye under dim light, and the animals were maintained for 2 more weeks in the same dark environment before they were moved to normal 12-hour light/12-hour dark vivarium cycling room light. The other eye remained uninjected. Subretinal injections were made under direct observation aided by a dissecting microscope under dim light. The injected retinal area was visualized by fluorescein-positive subretinal blebs demarcating the retinal detachment. Such detachments usually resolved within 1 to 2 days. Only animals with minimal surgical complications and initial retinal blebs occupying more than half the retina were retained for further evaluation.[26] Approximately 20 *rd10* mice met these criteria, which allowed at least three animals for each experiment. After all injections, 1% atropine eye drops and neomycin/polymyxin B/ dexamethasone ophthalmic ointment were given.

Electroretinography

Three weeks after subretinal injection (P35; 1 week after the move to cyclic light environment), a semiautomated ERG recording instrument adapted for rodent analysis (Jaeger/Toennies) was used for ERG examination. All testing was performed in a climate-controlled and electrically isolated dark room with animals placed on a 37°C warming pad. After overnight dark adaptation, mice were anesthetized by ketamine (72 mg/kg)/xylazine (4 mg/kg) intraperitoneal injection in a dark room under dim red light illumination. Corneas were anesthetized with a drop of 0.5% proparacaine hydrochloride, and the pupils were dilated with 1% atropine and 2.5% phenylephrine hydrochloride. Small contact lenses scaled

to mice with gold wire loop electrodes were placed on each cornea with a drop of 2.5% methylcellulose to maintain corneal hydration and to promote conductivity. A silver wire reference electrode was placed subcutaneously between the eyes, and a ground electrode was placed subcutaneously in a hind leg. For light-adapted electroretinography, the animals were put under a background light of 100 cd · s/m^2 for 5 minutes before the recording. Two days after ERG examination, almost all injected *rd10* mice were killed for morphologic and biochemical examination; the exception was one animal with almost 100% initial retinal detachment and minimal injection-related damage that was kept for another 2 weeks in a cyclic light environment for further ERG examination.

Immunocytochemistry for PDE*β* Expression

Treated *rd10* mice were killed 2 days after ERG examination for biochemical and morphologic examination. Eyes from treated and untreated *rd10* mice, along with age-matched C57BL/6J mice, were enucleated, and the eyecups and frozen sections were processed as described previously.[29] Retinal sections were permeabilized with 0.1% Triton X-100, rinsed in PBS, blocked in 20% normal goat serum (NGS), and incubated overnight at 4°C in a rabbit polyclonal anti–mouse PDE*β* antibody (ABR-Affinity BioReagents, Golden, CO), diluted 1:400 in 20% NGS. This antibody reacts with human and mouse PDE*β* protein. After three rinses with 0.1 M PBS, sections were incubated in goat anti–rabbit IgG conjugated with Texas Red (1:300; Molecular Probes, Eugene, OR) and DAPI (1:100; Molecular Probes, Eugene, OR) for 2 hours, followed by 3 rinses with 0.1 M PBS. Sections were then mounted with coverslips before fluorescence photography.

Western Blot Analysis

For PDE*β* measurements, eyecups were carefully dissected from treated and untreated *rd10* eyes and age-matched normal C57BL/6J eyes, pooled into separate groups (injected, uninjected, and normal, respectively), and homogenized by sonication in a buffer containing 0.23 M sucrose, 2 mM EDTA, 5 mM Tris-HCl (pH 7.5), and 0.1 mM phenylmethylsulfonyl fluoride. Samples were then centrifuged, and supernatants were collected. Protein concentrations were determined using a protein assay kit (Coomassie Plus; Pierce, Rockford, IL). After the addition of loading buffer (100 mM Tris-HCl [pH 6.8], 4% SDS, 20% glycerol, 200 mM dithiothreitol, 0.02% bromophenol blue), an equal amount (25 μg) of each sample was resolved by SDS-PAGE (10% Tris-glycine gel) and electrotransferred to a polyvinylidene difluoride membrane (Immobilon P; Millipore, Bedford, MA). The membrane was blocked with 5% horse serum in PBS and incubated overnight with thesame PDE*β* polyclonal antibody. The blot was then washed three times in PBS containing 0.05% Tween-20 (PBST) and was incubated with an anti–mouse IgG–conjugated alkaline phosphatase secondary antibody for 30 minutes at room temperature. After another wash in PBS, the blot was developed with a color assay using nitro blue tetrazolium and 5-bromo-4-chloro-3-indolyl phosphate. Treated and untreated *rd10* and normal C57BL/6J samples were compared on the same blot with *β*-actin as an internal loading control.

Histology and Morphometry

Structural evaluation of the treated and untreated eyes has been described.[26,29] Treated and untreated eyes from *rd10* mutant mice were enucleated, and eyecups were prepared for light and electron microscopic examination.

Visually Guided Behavioral Test

The water maze visually guided behavioral test has been described previously by us.[26] Briefly, 2 weeks after injection, one eye–treated *rd10* mice reared in a dark environment, together with age-matched untreated *rd10* and normal C57 mice, were initially trained in a

plastic water tank with a platform positioned in a well-lit room. Training consisted of three blocks of four trials per day for 4 consecutive days. During each trial, the mouse was placed in the water from one of four equally spaced start locations. Behavioral data were acquired as the latency to escape to the platform during the training trials. After training in the well-lit room, the rod function of dark-adapted mice was measured using the same procedure but under very dim light (not detectable with the Datalogging Light Meter, model 401036; Extech Instruments, Waltham, MA).

Results

To maintain *rd10* mice, we initially used lighting conditions that would allow a rate of retinal degeneration sufficiently slow for testing of a gene therapy approach. To that end, we maintained late-term pregnant *rd10* females in a continuously dark room, except for husbandry at 5 lux or less, and then raised the pups under the same conditions. Light microscopic images of retinas from 4-week-old *rd10* reared in a normal 12-hour light/12-hour dark cyclic light environment and from *rd10* mice raised in dim light are compared in Figure 1. Approximately three layers of photoreceptors and minimal outer segments remained in mice reared in vivarium cyclic light, whereas the outer nuclear layer (ONL) was nearly normal in dark-reared *rd10* mice. Thus, only dark-reared *rd10* mice were used to test for therapy.

Electrophysiological Rescue

At P14, *rd10* mice were subretinally injected with AAV5-smCBA-PDEβ. Three weeks after treatment (1 week after removal of mice to a cyclic light environment), *rd10* mice were examined by dark-adapted and light-adapted electroretinography. Larger dark- and light-adapted ERG responses were evident in vector-treated eyes. When the stimulus intensity was 2.68 cd · s/m^2, the average dark-adapted ERG b-wave amplitudes in PDEβ treated *rd10* eyes were 200 ± 20 μV (Fig. 2A; $n = 3$), which was 37% of the isogenic wild-type mice (544 ± 89 μV; $n = 3$) and approximately threefold higher than in contralateral untreated eyes (70 ± 40 μV; $n = 3$). Paired *t*-test analysis showed significantly smaller dark-adapted b-wave amplitudes in untreated *rd10* eyes compared with C57 eyes ($P < 0.01$). Although statistically not as good as those in normal C57 eyes ($P < 0.05$), dark-adapted b-wave amplitudes were significantly improved in treated *rd10* eyes compared with those in untreated *rd10* eyes ($P < 0.05$). Light-adapted ERG b-wave amplitudes elicited with a flash intensity of 12 cd · s/m^2 were 118 ± 25 μV in normal, 109 ± 23 μV in treated *rd10*, and 66 ± 29 μV in untreated *rd10* eyes (Fig. 2B). Statistical analysis showed similar light-adapted ERG b-wave amplitudes ($P = 0.6$) between normal C57 and treated *rd10* eyes 3 weeks after injection ($n = 6$), whereas a significant difference was found between treated and untreated *rd10* eyes ($P < 0.05$; $n = 6$). Figure 2C–D shows a representative *rd10* mouse 5 weeks after one eye received subretinal vector at P14 (P49, 3 weeks after returning to cyclic light environment). In the untreated *rd10* eye, dark-adapted ERG responses were minimal (Fig. 2C), whereas the light-adapted b-wave amplitudes (Fig. 2D) were approximately 25% of the wild-type controls elicited with flash intensity of 12 cd · s/m^2. In the treated *rd10* eye, approximately 22% of the normal dark-adapted b-wave (Fig. 2C) and 82% of the normal light-adapted b-wave amplitudes elicited with flash intensity of 2.68 cd · s/m^2 (Fig. 2D) persisted. In time domain, the implicit times of the dark- and light-adapted ERG b-waves were approximately 75 ms (2.68 cd · s/m^2) and 45 ms (12 cd · s/m^2), respectively. In the treated *rd10* mouse eye, the implicit time of the dark-adapted b-wave was comparable to that of the wild type mouse; however, the implicit time of the light-adapted b-wave was approximately 60 ms, which is similar to that for the untreated eye but is approximately 15 ms longer than for the normal control. Finally, as additional controls, we tested subretinal AAV5-smCBA-GFP and PBS in *rd10*

eyes. No rescue effects were observed in these eyes, indicating rescue is not a consequence of the injection procedure itself (data not shown).

PDEβ Expression

Two days after the final ERG examination, PDEβ expression was assayed by immunohistochemistry of retinal sections in *rd10* eyes. Strong PDEβ staining is evident in the outer segments of treated eyes, similar to that seen in the normal C57 retinas (Fig. 3A). Inner segment staining is weak but detectable in treated eyes. In contrast, no PDEβ expression was observed in any portion of the untreated retina from the same *rd10* mouse. To confirm the identity of this signal, Western blot analysis showed the presence of PDEβ protein in treated *rd10* eyes but not in untreated contralateral eyes (Fig. 3B). We estimated that the level of PDEβ from pooling protein extracts from five treated eyes was slightly less than that seen from a single wild-type eye and, therefore, further estimated that we restored an average of 10% to 15% of the normal level of PDEβ in treated *rd10* eyes compared with that in age-matched uninjected normal eyes.

Structural Rescue

Vector-treated *rd10* eyes were assessed for the degree of structural rescue that accompanied ERG preservation. In light microscopic images at low magnification, it is apparent that most treated *rd10* retinas maintained a relatively normal ONL, whereas in the untreated eye of the same *rd10* mouse, the ONL contained few and difficult-to-visualize photoreceptor cell bodies (Fig. 4A). Images at higher magnification showed that a typical treated retina retained approximately 30% of its outer segment length compared with the wild-type retina and approximately 60% of its ONL thickness. The best results showed that up to 90% of ONL nuclei and more than 50% of the outer segment length was preserved by treatment (Fig. 4B). In contrast, in the entire untreated eye from the same mouse, at most only one to three rows of ONL nuclei remained, with no outer segments evident in the central retina and only residual outer segment membrane in the periphery (Fig. 4B). Electron microscopic images confirmed that the treated eye contained shortened but normal-appearing outer segments. In the contralateral untreated *rd10* eye, outer segments were absent or only residual structures remained, resulting in the outer limiting membrane (OLM) being nearly opposed to the RPE layer (Fig. 4C). A limited number of electron-dense photoreceptor nuclei remained beneath the OLM in the untreated *rd10* retina (Fig. 4C, lower left).

Rescue of Visually Guided Behavior

To determine whether the observed electrophysiological, biochemical, and structural preservation of the *rd10* retina on vector treatment led to improvement in vision that may be useful in a behavioral sense, we tested several *rd10* mice in a visually guided water maze task.[26] After 4 days of training, analysis of times to find the platform under very dim light conditions showed that normal C57 mice averaged 9.7 ± 0.8 seconds, *rd10* mice vector treated in one eye averaged 22.6 ± 4.2 seconds, and untreated *rd10* mice averaged 51.5 ± 1.1 seconds (Fig. 5). Statistical analysis showed significant deterioration on the vision-guided performance task in untreated *rd10* mice ($n = 3$) compared with normal C57 mice ($n = 3$; $P < 0.0001$). Although not as quick as normal C57 mice ($P = 0.0192$), *rd10* mice ($n = 4$) treated in just one eye showed significantly improved vision-guided performance compared with untreated littermates ($P = 0.0003$).

Discussion

The *rd10* mouse is a funduscopically identified RD mouse that has a recessive PDEβ mutation similar to one type of human retinitis pigmentosa.[18] Although there is an early recordable scotopic a-wave, rod photoreceptor degeneration initiates at about P18 and

progresses to only two to three ONL nuclei remaining at P30.[19] In fact, photoreceptor outer segments in *rd10* mice are never fully developed when animals are reared in a normal cyclic room light environment. This presents a significant challenge for gene therapy because we estimate it takes 1 to 2 weeks for AAV5-smCBA-PDEβ to express sufficient PDEβ protein for physiological demand in the *rd10* retina, suggesting that the best timing for vector delivery would be P0 to P5 in *rd10* mice. However, mouse eyes at this age have not yet opened and can be easily damaged by any invasive procedure. Transscleral subretinal injection is still possible in neonatal mice. Typically, however, less than 40% of the retina can be transfected, and many injection-related complications have been noted.[13,15,17,27] Successful subretinal injection in this sense requires two elements—a relatively large transfected retinal area that can be reached by transcorneal subretinal injection and minimal injection-related damage—both difficult to achieve in very young mice but more easily achieved in older mice. Hence, the need is apparent to slow degeneration in the *rd10* retina sufficiently to allow more mature animals to be tested while still allowing time for vector to express therapeutic levels of PDEβ protein before degeneration is too far advanced. Fortunately, we confirmed the observation that retinal degeneration could be slowed if *rd10* mice are reared in darkness.[19] The effect of light on accelerating retinal degeneration has been noted for the T4R rhodopsin dog[30] and the T17M rhodopsin mouse.[31] The observation we have made, that light also accelerates degeneration in mutant PDEβ mice, generalizes the phenomenon beyond rhodopsin mutations affecting retinal integrity.

Gene therapy improved dark- and light-adapted ERGs in *rd10* mouse. In particular, the light-adapted b-wave amplitudes in the treated *rd 10* mice were comparable to those of the normal wild-type mice. However, the timing of the light-adapted ERG b-wave of the treated *rd10* eye remains delayed. Further investigation will be necessary to clarify whether the second exposure during ERG examination in P14+5W *rd10* mouse accelerated the b-wave peak delay, whether it was related to the cone degeneration in *rd10* mouse, or both. The general lack of a rescue effect in previous PDEβ gene therapy attempts using the *rd1* mouse[13–15] raises several questions about why the *rd1* mouse did not respond well to gene replacement therapy though the *rd10* mouse, tested here, did. First, is there something specific to recessive PDEβ mutations that confers the property of cryptic dominance when attempting gene replacement therapy, thus preventing more effective gene replacement therapy? Given that we clearly show an upregulation of the PDEβ vector transgene in treated retinas and structural, concomitant with electrophysiological and vision-guided behavioral preservation, this would seem to argue otherwise. However, a cryptically dominant property of the *rd1* mutation not shared by the *rd10* mutation cannot be eliminated. Second, is it simply that retinal degeneration in the *rd1* mouse is too early and too rapid for AAV-vectored gene therapy to be effective? We believe this may be at least partially the case because slowing the degenerative process in the *rd10* mouse through dark rearing allowed therapy to become more effective. Third, and related to the first two questions, are relatively well-developed photoreceptor outer segments necessary for PDEβ gene therapy to be successful? This may also be partially true. If what is needed for successful PDEβ therapy is a substantial fraction of the normal amount of PDEβ in the presence of other outer segment proteins—perhaps most important the major binding partners of PDEβ, PDEα, and PDEγ—then the expression of vectored PDEβ in dark-reared *rd10* animals with normal outer segments is internally consistent with this hypothesis. Thus, it seems plausible that our ability to preserve photoreceptor structure and function in the *rd10* mouse reflects its slower rate of degeneration, which allows vector-expressed PDEβ to be stably integrated into a normal complement of preexisting outer segment phototransduction components.

Although longer term rescue will clearly be required if gene replacement therapy for PDEβ-based RP is a viable therapeutic option, results reported here using the dark-reared *rd10* mouse demonstrate that relatively complete rescue is possible. This model, therefore, seems

well suited for modified gene therapy approaches that may express wild-type PDEβ more rapidly than current vectors and may offer the potential for longer term functional rescue. If achieved, this would represent a hopeful development for one of the more common and aggressive forms of human RP.

Acknowledgments

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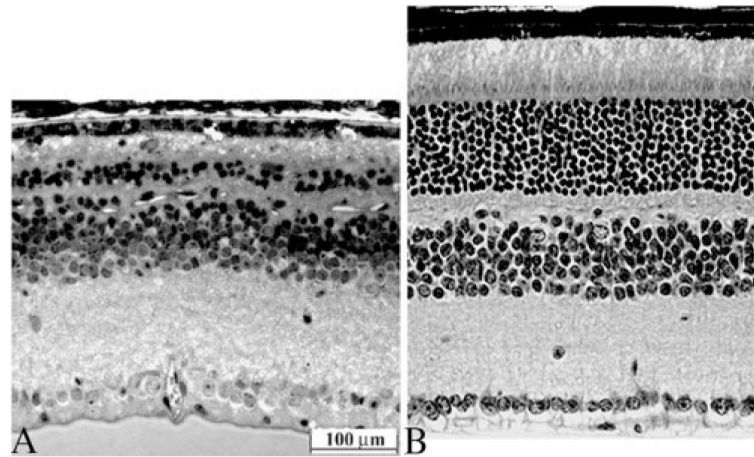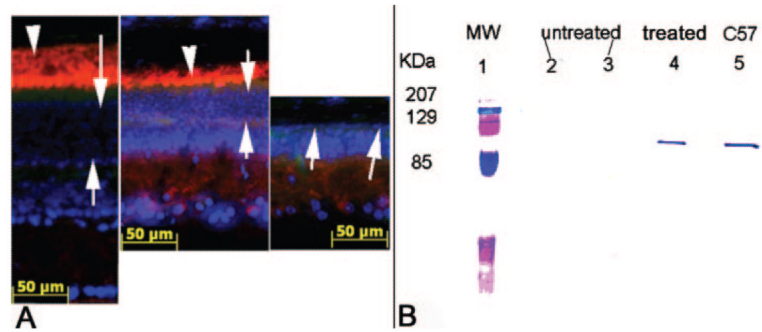
Figure 1.
Light microscopic images of a 4-week-old *rd10* mouse reared in normal cyclic light environment (*left*) compared with very dim light (*right*). Both images are from equivalent central regions of retina. Only two to three layers of ONL nuclei with residual outer segment material remain in the cyclic light–reared animal. In the dim light–reared animal, a nearly normal complement of 9 to 10 ONL nuclei are evident with clearly improved inner and outer segment morphology.
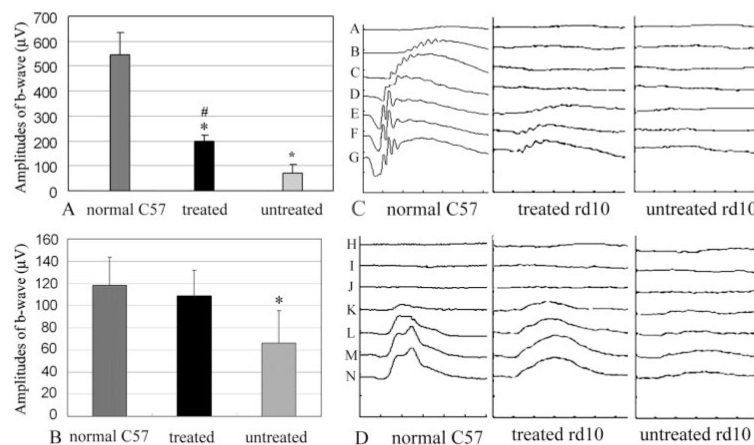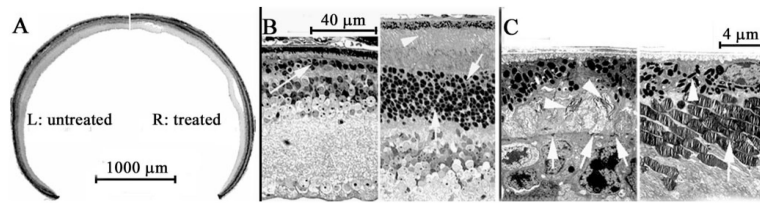
Figure 2.
Scotopic and photopic ERGs in normal C57 and one eye–treated *rd10* mice. (**A**) Averaged, scotopic b-wave amplitudes at 2.68 cd · s/m² flash intensity in normal C57 (*left*), treated (*middle*), and untreated *rd10* (*right*) eyes. (**B**) Averaged photopic b-wave amplitudes at 12 cd · s/m² flash intensity in normal C57 (*left*), treated (*middle*), and untreated (*right*) eyes from *rd10* mice 3 weeks after treatment at P14. (**C**) Representative of scotopic ERG waveforms elicited from a set of input single-flash intensities. (A: 0.1 mcd · s/m²; B: 1.0 mcd · s/m²; C: 10 mcd · s/m²; D: 100 mcd · s/m²; E: 1.0 cd · s/m²; F: 1.5 cd · s/m²; G: 2.68 cd · s/m²) from a normal C57 eye (*left*) and a *rd10* eye 5 weeks after treatment at P14 (*middle*) compared with the untreated eye (*right*) from the same 7-week-old *rd10* mouse. *Y* axis: 250 μV/Division; *X* axis: 25 ms/Div. (**D**) Representative of photopic ERG waveforms from a normal C57 eye (*left*), a treated (*middle*), and an untreated (*right*) eye of an *rd10* mouse 5 weeks after treatment at P14. *Y* axis: 100 μV /Div ; *X* axis: 20 ms/Div. Input flash intensities are H: 1 mcd · s/m²; I: 10 mcd · s/m²; J: 100 mcd · s/m²; K: 1 cd · s/m²; L: 5 cd · s/m²; M: 10 cd · s/m²; N: 12 cd · s/m². Symbols and bars represent mean ± SEM. *Significant difference between *rd10*-untreated and *rd10*-treated and between *rd10*-untreated and normal C57 mice. #Significant difference between *rd10*-treated and normal C57 mice.
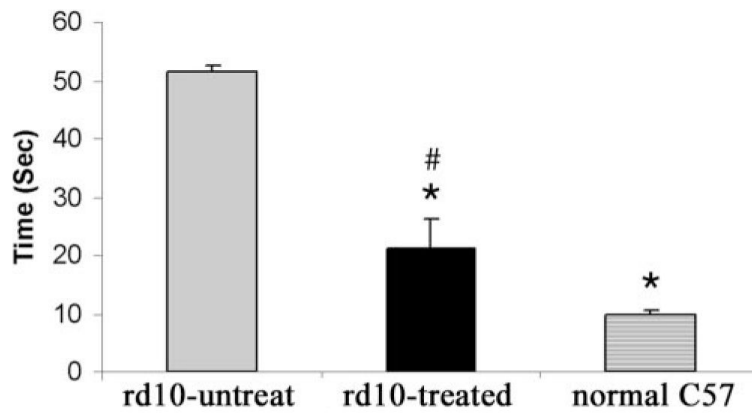
Figure 3.
Comparison of PDEβ expression in C57BL/6J and *rd10* mice. (**A**) PDEβ immunostaining (*red*) in a 5-week-old uninjected normal C57BL/6J eye (*left*), treated eye (*center*), and untreated eye (*right*) from one *rd10* mouse. Nuclei were stained with DAPI (*blue*). *Arrows*: photoreceptor. *Arrowheads*: outer segments of photoreceptor. (**B**) Western blot showing PDEβ from 5-week-old AAV5-smCBA–PDEβ treated and untreated *rd10* eyes and an untreated age-matched normal C57BL/6J control eye. *Lane 1*: molecular weight marker; *lanes 2* and *3*: five pooled, untreated *rd10* retinas; *lane 4*: five pooled, treated *rd10* retinas; *lane 5*: one normal C57BL/6J retina.

Figure 4.
Light microscopic (LM) images of treated and untreated eyes from one *rd10* mouse. (**A**) LM images at low magnification showing an untreated (*left*) and a treated (*right*) eye from the same *rd10* mouse. (**B**) LM images from the central retina of both eyes of an *rd 10* mouse 3 weeks after P14 injection with rAAV5-smCBA-PDEβ into one eye. *Left*: untreated eye. *Right*: treated eye. *Arrows*: photoreceptor nuclei. *Arrowhead*: photoreceptor outer segments. (**C**) Electron microscopic images from a 5-week-old *rd10* mouse with one eye treated with AAV5-smCBA-PDEβ at P14. *Left*: untreated eye. *Arrowheads*: residues of outer segments. *Arrow*: outer limiting membrane. *Right*: treated eye. *Arrowhead*: RPE cells. *Arrow*: outer segments.

Figure 5.
Water maze visually guided behavioral test showed the average times to the platform among untreated *rd10* (*left*, *gray bar*, *n* = 3), treated *rd10* (*middle*, *black bar*, *n* = 4), and age-matched normal C57 (*right*, *solid diamonds bar*, *n* = 3) mice. Symbols and bars represent mean ± SEM. *Significant difference between *rd10*-untreated and *rd10*-treated, and *rd10*-untreated and normal C57 mice. #Significant difference between *rd10*-treated and normal C57 mice.