Transgenic Mice Over-Expressing RBP4 Have RBP4-Dependent and Light-Independent Retinal Degeneration

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Submitted: April 24, 2017
Accepted: July 18, 2017

Citation: Du M, Phelps E, Balangue MJ, et al. Transgenic mice over-expressing RBP4 have RBP4-dependent and light-independent retinal degeneration. Invest Ophthalmol Vis Sci. 2017;58:4375–4383. DOI:10.1167/iovs.17-22107

PURPOSE. Transgenic mice overexpressing serum retinol-binding protein (RBP4-Tg) develop progressive retinal degeneration, characterized by microglia activation, yet the precise mechanisms underlying retinal degeneration are unclear. Previous studies showed RBP4-Tg mice have normal ocular retinoid levels, suggesting that degeneration is independent of the retinoid visual cycle or light exposure. The present study addresses whether retinal degeneration is light-dependent and RBP4-dependent by testing the effects of dark-rearing and pharmacological lowering of serum RBP4 levels, respectively.

METHODS. RBP4-Tg mice reared on normal mouse chow in normal cyclic light conditions were directly compared to RBP4-Tg mice exposed to chow supplemented with the RBP4-lowering compound A1120 or dark-rearing conditions. Quantitative retinal histological analysis was conducted to assess retinal degeneration, and electroretinography (ERG) and optokinetic tracking (OKT) tests were performed to assess retinal and visual function. Ocular retinoids and bis-retinoid A2E were quantified.

RESULTS. Dark-rearing RBP4-Tg mice effectively reduced ocular bis-retinoid A2E levels, but had no significant effect on retinal degeneration or dysfunction in RBP4-Tg mice, demonstrating that retinal degeneration is light-independent. A1120 treatment lowered serum RBP4 levels similar to wild-type mice, and prevented structural retinal degeneration. However, A1120 treatment did not prevent retinal dysfunction in RBP4-Tg mice. Moreover, RBP4-Tg mice on A1120 diet had significant worsening of OKT response and loss of cone photoreceptors compared to RBP4-Tg mice on normal chow. This may be related to the very significant reduction in retinyl ester levels in the retina of mice on A1120-supplemented diet.

CONCLUSIONS. Retinal degeneration in RBP4-Tg mice is RBP4-dependent and light-independent. Keywords: serum retinol-binding protein, retinal degeneration, RBP4

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Serum retinol-binding protein (RBP4) is the protein responsible for binding and transporting retinol (vitamin A) through the blood stream to target tissues.1–4 RBP4 is especially important for delivering retinol to the retinal pigment epithelium,5 where retinol is used in a biochemical pathway known as the “retinoid visual cycle” to generate the light-responsive visual chromophore.6–9 RBP4-knockout mice (RBP4-KO) have reduced retinol uptake into the retina, resulting in reduced levels of visual chromophore and impaired vision, although vision can be restored to normal through administration of sufficient dietary vitamin A.5 Thus, RBP4 supports optimal visual function, but is not completely essential for vision, since retinol can still get into the retina through RBP4-independent pathways.

The classical function of RBP4 in retinoid trafficking has been well characterized;1–5 however, several clinical studies have found that elevated concentrations of RBP4 in serum is correlated with systemic disease, including obesity,10,11 insulin resistance,10–15 and type 2 diabetes.11,15 Further studies have shown that high concentrations of RBP4 elicit retinol-independent proinflammatory activity, which contributes to adipose tissue inflammation and insulin resistance in mice.16,17 We recently discovered that mice overexpressing RBP4 (RBP4-Tg) develop early-onset progressive retinal degeneration,18 yet the underlying mechanisms are unclear.

Retinal degeneration in RBP4-Tg mice is characterized by microglia activation and neuroinflammatory expression of interleukin (IL)-18 in the retina.18 Retinal degeneration in RBP4-Tg mice begins as early as 1 month of age and deteriorates rapidly so that by 6 months of age ERG responses are very significantly and severely reduced.18 Importantly, RBP4-Tg mice aged up to 6 months have no signs of systemic disease, and are normoglycemic with normal body weight and insulin responses,18 which indicates that retinal degeneration is caused by a specific effect on the retina rather than an indirect result of systemic disease. We found that RBP4-Tg mice retinae have normal steady-state retinoid profiles and only slightly elevated bis-retinoid A2E levels,18 suggesting that retinal degeneration occurs through a mechanism that is unrelated to retinoid trafficking, and likely caused by the proinflammatory action of RBP4. The present study investigated whether the classical function of RBP4 in retinoid trafficking plays a role in retinal degeneration in RBP4-Tg mice by dark-rearing mice to inhibit the retinoid visual cycle. In addition, we tested whether pharmacological lowering of serum RBP4 levels can alleviate retinal degeneration in RBP4-Tg mice.
METHODS

Mice

RBP4-Tg mice, which overexpress human RBP4 under control of the mouse muscle creatine kinase (MCK) promoter on a C57BL/6J background, have been described previously.\(^\text{15}\) Both RBP4-Tg and RBP4-KO mice were kindly provided by Loredana Quadro. All animal studies were approved by the Institutional Animal Care and Use Committee of the University of Oklahoma Health Sciences Center, and adhered to the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research. All studies were performed on age-, sex-, and strain-matched wild-type controls. Both sexes were used in all studies, and no sex-dependent differences in phenotype were observed. Importantly, RBP4-Tg mice were confirmed to be free of the retinal degeneration rd8 mutation that is known to be present in some C57BL/6 colonies (data not shown).

Unless otherwise noted, mice were reared under normal cyclic light conditions (12-hour light/12-hour dark), with cage rack light intensities of 9.5 to 40 lux. Dark-reared mice were born and reared in a specially designed dark room, and only exposed to filtered dim red light to allow for staff to provide proper care. Unless otherwise noted, mice were fed a standard chow diet (Labdiet 5001) ad libitum. This diet contains a sufficient amount of vitamin A (15 IU g\(^{-1}\)). For studies involving A1120, A1120 was purchased from Tocris Biosciences, United Kingdom (catalog no. 5793). Standard mouse chow (Labdiet 5001) was supplemented with A1120 at 0.03% or 0.05% (0.3 or 0.5 g A1120 per Kg chow, prepared by Envigo, United Kingdom), and mice were fed ad libitum. A1120 diet administration began at weaning (P21), as testing showed no A1120-mediated lowering of serum RBP4 in pups when the maternal diet was supplemented with A1120 prior to weaning.

Mouse serum was collected by superficial temporal vein puncture from live mice that had fasted for 6 hours. ELISA kits for mouse RBP4 (catalog #MBR400; R&D Systems, Minneapolis, MN, USA) and human RBP4 (catalog# DBR400; R&D Systems) were used to quantify target molecules in serum.

 Electrophoretography (ERG)

ERG was performed as described previously.\(^\text{18}\) Mice were weighed the day prior to ERG test and dark adapted overnight. Thirty minutes prior to test, one drop of 1% cyclogyl was delivered to each cornea for pupil dilation. Mice were anesthetized with an intraperitoneal injection of a cocktail of ketamine/xylazine at 85/14 mg/kg, respectively. Body temperature was maintained at 37°C using a heating pad. Pupsicles were diluted a second time with Phenylephrine Hydrochloride in the dark under dim red light, and eyes were enucleated and stored at −80°C protected from light. All further sample processing and HPLC was performed in the dark under dim red light. The whole eyes were homogenized by glass grinder in lysis buffer [10 mM NH\(_2\)OH, 50% ethanol, 50% 2-(N-morpholino)ethanesulfonic acid, pH 6.5], and retinoids were extracted with hexane. Solvent was evaporated under argon gas, and dried retinoid samples were resuspended in 200 \(\mu\)L mobile phase (11.2% ethylacetate, 2.0% dioxane, 1.4% octanol, 85.4% hexane) and injected into the HPLC machine (515 HPLC pump, Waters Corp., Milford, MA, USA) at an isocratic flow rate of 1 mL/min for separation using a normal phase 5-μm column (Lichosphere SI-60; 4.6 mm inner diameter \(\times\) 250 mm length; Alltech, Deerfield, IL, USA). Each retinoid isomer was quantified from the area of its corresponding peak, determined by using synthetic purified retinoid standards for calibration (empower software; Waters Corp.).

For bleach-recovery ERG measurements, mice were dark-adapted overnight and then a prebleach ERG measurement was taken at flash intensity of 0.04 (S)cd.s/m\(^2\). Then mice were exposed to a light at 500 cd/m\(^2\) for 2 minutes to “bleach” ~89% to 90% of visual pigment. The postbleach ERG measurements [0.04 (S)cd.s/m\(^2\)] were taken immediately after the “bleach,” and every 4 minutes thereafter for up to 40 minutes.

Quantitative Histological Analyses of Retinal Thickness and Immunohistochemistry

A blood needle was used to scorch the superior side of the cornea to demarcate the vertical meridian, and eyes were enucleated with part of the optic nerve still attached. Eyes were fixed in 4% paraformaldehyde for 24-hours, subsequently transferred into PBS, then dehydrated and paraffin-embedded for sectioning along the superior-inferior retinal axis. Sections were deparaffinized, stained with hematoxylin and eosin, and images were scanned at 40X magnification on a Ventana Coreo Au Slide Scanner (Tissue Sciences Facility, University of Nebraska Medical Center). Scanned images underwent quantative analysis using Ventana image viewer software (Ventana Medical Systems, Inc., Tucson, AZ, USA). Beginning at the optic nerve head and extending into the retinal periphery in 250-μm increments, thickness of the total retina was measured.

For immunohistochemistry, sections were deparaffinized, and antigen retrieval was performed using 10 mM sodium citrate pH 6.0. Then sections were permeabilized in PBS containing 0.03% Triton X-100 (PBST) for 15 minutes. Sections were coated in blocking solution (PBST with 5% bovine serum albumin) for 1 hour before incubation overnight at 4°C in primary antibodies diluted in blocking buffer. After sections were washed in PBST, they were incubated with appropriate fluorophore-conjugated secondary antibodies for 1 hour at room temperature. Then sections were washed in PBST, and 0.1% Sudan black in 70% ethanol was applied to the sections to reduce background autofluorescence. The sections were then rinsed, and Vectashield mounting medium (Vector Laboratories, Burlingame, CA, USA) containing 4’,6-diamidino-2-phenylindole (DAPI) was applied as a coverslip was placed over the sections. Sections were imaged at 20X magnification using a Zeiss Observer Z1 microscope. The following EMD Millipore (Billerica, MA, USA) antibodies were used: cone arrestin (catalog no. AB15282), cone S-opsin (catalog no. ab5407), and cone M-opsin (catalog no. ab5405).

Quantification of Visual Cycle Retinoids and Bis-Retinoid A2E in Mouse Eyes

Visual cycle retinoids were quantified as described previously.\(^\text{16}\) Mice were dark-adapted overnight for 16 hours, killed in the dark under dim red light, and eyes were enucleated and stored at −80°C protected from light. All further sample processing and HPLC was performed in the dark under dim red light. The whole eyes were homogenized by glass grinder in lysis buffer [10 mM NH\(_2\)OH, 50% ethanol, 50% 2-(N-morpholino)ethanesulfonic acid, pH 6.5], and retinoids were extracted with hexane. Solvent was evaporated under argon gas, and dried retinoid samples were resuspended in 200 \(\mu\)L mobile phase (11.2% ethylacetate, 2.0% dioxane, 1.4% octanol, 85.4% hexane) and injected into the HPLC machine (515 HPLC pump, Waters Corp., Milford, MA, USA) at an isocratic flow rate of 1 mL/min for separation using a normal phase 5-μm column (Lichosphere SI-60; 4.6 mm inner diameter \(\times\) 250 mm length; Alltech, Deerfield, IL, USA). Each retinoid isomer was quantified from the area of its corresponding peak, determined by using synthetic purified retinoid standards for calibration (empower software; Waters Corp.).
Bis-retinoid A2E was quantified as described previously. Mice were reared either under normal cyclic light or in a dark room under dim red light. All mice were fed standard chow ad libidum. At 9 months of age, mice were killed, eyes were enucleated, and the eyecup (RPE, sclera, and choroid) was dissected out. A total of four eyecups (from two mice of the same genotype and sex) were pooled to generate a single sample for HPLC measurement. Eyecups were stored at −80°C until analysis. Samples were homogenized in a glass grinder in PBS, and bis-retinoids were extracted three times using chloroform/methanol (2:1 vol/vol). The pooled organic phases were dried under a stream of argon gas and resuspended in 100 μL methanol. A2E was separated using a mobile phase gradient of methanol in water (85%–96% methanol + 0.1% trifluoroacetic acid) through a C18 reverse phase column (3.5 μM, 4.6 × 150 mm, Waters Corp.) at a flow rate of 1 mL/min. A Waters 2996 photodiode array detector was used to monitor absorbance of A2E at 430 nm. A2E levels were quantified from the area of the peak using purified A2E standard for calibration (Empower software; Waters Corp.).

Optokinetic Tracking (OKT) Analyses. As described previously, visual function was measured using a virtual OKT system (OptoMotry, CerebralMechanics, Inc., Medicine Hat, Alberta, Canada) designed for rapid, quantifiable behavioral measurements of spatial vision in a virtual environment. All OKT experiments were performed using an OptoMotry designed for rodent use (CerebralMechanics, Inc.). The animals were placed on a platform surrounded by four computer monitors forming a square inside an enclosed box. The monitors display continuous vertical sine wave gratings rotating across the monitors at 12/s, which appear to the animal as a virtual three-dimensional rotating cylinder. The animal’s ability to visualize the sine wave was monitored via a video camera positioned directly above the animal to display an image perpendicular to the animal’s field of vision. The rotation of the virtual cylinder was constantly centered at the animal’s viewing position to ensure a consistent viewing distance. Tracking movements were identified as slow, steady head movements in the direction of the rotating grating. For measurements of spatial frequency threshold, the mice were tested at a range of spatial frequencies from 0.034 to 0.664 cyc/deg. The OptoMotry device employs a proprietary algorithm to accept the input from the masked observer and automatically adjusts the testing stimuli based upon whether the animal exhibited the correct or incorrect tracking reflex. All measurements of contrast threshold were performed at a spatial frequency threshold of 0.064 cyc/deg. The contrast sensitivity was calculated as a reciprocal of the Michelson contrast from the screen’s luminance (maximum − minimum)/ (maximum + minimum).

Statistical Analysis

Data are presented as mean ± standard deviation. Statistical analyses were conducted using Prism 4 software (La Jolla, CA, USA) with 1-way ANOVA using Tukey’s post hoc analysis to compare differences among three or more groups. A value of P < 0.05 was accepted as significant.

RESULTS

RBP4-Tg Mice Have Normal ERG Bleach-Recovery Kinetics

Since we have previously shown that RBP4-Tg mice retinae have a slight elevation in toxic bis-retinoid A2E levels, it could be that RBP4-Tg mice have an increased level or rate of retinoid visual cycle activity. In order to estimate visual chromophore regeneration kinetics, we performed ERG bleach-recovery experiments, in which mice were exposed to a prolonged light stimulus to effectively bleach >85% of light-responsive visual pigments, followed by measurement of retinal response to light stimuli every 4 minutes. As shown previously, RBP4-Tg mice have a significantly reduced scotopic b-wave amplitude prebleach (Fig. 1A), and the bleaching protocol effectively
reduced the postbleach ERG response by 85% to 90% so that wild-type and RBP4-Tg mice had similar scotopic b-wave amplitude responses postbleach (Fig. 1A). ERG measurements during the recovery phase show no statistical difference in scotopic b-wave recovery kinetics between wild-type and RBP4-Tg mice (Fig. 1B). These data establish that RBP4-Tg mice have normal visual pigment regeneration kinetics.

**Retinal Degeneration Is Light-Independent in RBP4-Tg Mice**

To determine whether retinoid visual cycle activity and its toxic by-products, such as bis-retinoid A2E, contribute to retinal degeneration in RBP4-Tg mice, the retinoid visual cycle was inhibited by dark-rearing mice. As expected, dark-rearing had no effect on serum RBP4 levels, and RBP4-Tg mice at 6 months of age maintained a ~8-fold increase in serum RBP4 compared to wild-type (Fig. 2A). As shown previously, RBP4-Tg mice reared under normal cyclic light conditions have a slight but significant increase in bis-retinoid A2E levels in their eyecups by 9 months of age (Fig. 2B). As expected, dark-rearing effectively inhibited the retinoid visual cycle to prevent the elevation of A2E in RBP4-Tg eyecups (Fig. 2B). Despite the effectiveness of dark-rearing to inhibit A2E production, dark-rearing had no effect on ERG response or structural retinal degeneration in RBP4-Tg mice (Figs. 2C–F). Dark-reared RBP4-Tg mice had significantly reduced scotopic a- and b-wave and photopic b-wave responses compared to wild-type mice, and there was no statistically significant difference in ERG responses from RBP4-Tg mice reared in the dark versus normal cyclic light (Figs. 2C–E). Likewise, central retinal degeneration was very similar in RBP4-Tg mice reared in the dark versus normal cyclic light (Fig. 2F). These data demonstrate that retinal degeneration in RBP4-Tg mice is light-independent, and therefore unrelated to the retinoid visual cycle or the classical role of RBP4 in supplying retinol to the retinal pigment epithelium.

**Pharmacological Lowering of Serum RBP4 Prevents Retinal Degeneration in RBP4-Tg Mice**

To test whether pharmacological lowering of serum RBP4 can alleviate retinal degeneration in RBP4-Tg mice, mouse chow was supplemented with a nonretinoid RBP4 antagonist, A1120. The A1120 compound binds to the retinoid-binding pocket of RBP4, thereby blocking retinol-binding and promoting renal excretion of RBP4. A1120 supplementation chow significantly and dose-dependently reduced serum RBP4 levels in RBP4-Tg mice (Fig. 3A). In fact, the highest dose of A1120 (0.05%) resulted in serum RBP4 levels that were not statistically different from wild-type level (Fig. 3A). We found that the lower dose (0.03%) of A1120, which resulted in a 70% decrease in serum RBP4 level, was sufficient to prevent structural retinal degeneration in RBP4-Tg mice (Fig. 3B). These data show that structural retinal degeneration in RBP4-Tg mice is RBP4-dependent. However, the A1120 treatment did not block or reduce retinal dysfunction in RBP4-Tg mice, since there was no statistically significant difference in ERG results between RBP4-Tg mice on standard diet versus A1120-supplemented diet (Figs. 3C–E).

**A1120 Treatment Reduces Retinyl Ester Stores in the Retina, Impairs OKT, and Results in Loss of Cone Photoreceptors**

In an effort to understand why A1120-mediated lowering of serum RBP4 levels prevents structural retinal degeneration but not retinal dysfunction, we measured retinal retinoid profiles. As shown previously, RBP4-Tg mice had a significant increase in all-trans-retinal (Fig. 4A). As expected, the all-trans-retinal level was significantly reduced and similar to wild-type level in A1120-treated RBP4-Tg mice (Fig. 4A). The level of visual chromophore 11-cis-retinal was similar to wild-type in all groups of RBP4-Tg mice, regardless of A1120 treatment (Fig. 4A). However, RBP4-Tg mice treated with A1120 had a very statistically significant and severe reduction in retinyl esters stores in the retina, which was comparable to the retinyl ester level found in RBP4-knockout (RBP4-KO) mice (Fig. 4A). This finding suggests that the mice treated with A1120 have suboptimal retinol uptake into the retinal pigment epithelium.

Our previous study showed that the OKT response is reduced in RBP4-Tg mice, and we observed similar results in the present study (Figs. 4B, 4C). Surprisingly, the OKT response was very significantly and severely reduced in A1120-treated RBP4-Tg mice (Figs. 4B, 4C). Since the OKT response relies on high acuity bright light vision, which is mediated by cone photoreceptors, we performed immunohistochemical staining to evaluate cone distribution in the retina. We found that A1120-treated RBP4-Tg mice had a clear decline in the abundance of cones, based on the staining pattern of M- and S-opsins, as well as cone arrestin (Figs. 4D, 4E).

**Discussion**

This study definitively shows that retinal degeneration is light-independent in RBP4-Tg mice, thereby confirming that the classical function of RBP4 in retinoid trafficking is unrelated to the mechanisms of retinal degeneration in RBP4-Tg mice. We have previously shown that RBP4-Tg mice have retinal microglia activation and significant induction of IL-18 expression in the retina, indicating that neuroinflammation is a major feature of retinal degeneration in RBP4-Tg mice. In addition, numerous studies have shown that high concentrations of RBP4 exert proinflammatory effects in cells and tissues. Recently, we and others have shown that the proinflammatory effects of RBP4 in adipose tissue macrophages are largely mediated through activation of toll-like receptor 4 (TLR4). TLR4 is involved in the pathogenesis of different types of retinal degeneration. Retinal microglia, which are activated as early as 1 month of age in RBP4-Tg mice, express TLR4. Moreover, TLR4-mediated signaling has been shown to induce IL-18 mRNA and protein activation. Therefore, we speculate that RBP4 may activate TLR4 signaling in retinal microglia to release IL-18, but this is yet to be determined.

The present study also demonstrates that pharmacological lowering of serum RBP4 levels prevents retinal degeneration in RBP4-Tg mice (Figs. 3A, 3B), confirming that it is an RBP4-dependent phenomenon. However, the A1120 compound used for lowering serum RBP4 levels severely reduces retinyl ester stores in the retina by over 80%, to a level that is similar to RBP4-KO mice (Fig. 4A). Similar to our result, a previous study showed that 12 days of A1120 treatment depleted retinyl ester stores in the mouse retina by almost 30%. However, A1120 does not directly interfere with the RPE visual cycle activity by using bovine RPE microsomes to test isomerohydrolase (RP665) activity in the presence or absence of A1120. Rather, A1120 indirectly inhibits the RPE visual cycle activity by binding to serum RBP4 and reducing RBP4-mediated uptake of retinol by the RPE. Moreover, A1120 has less off-target effects compared to other RBP4-lowering compounds, such as Fenretinide [N-(4-hydroxyxyr-
Retinal degeneration in RBP4-Tg mice is light-independent. Wild-type (WT) and RBP4-Tg mice were reared in normal cyclic room light conditions or in a dark room. (A) Total RBP4 (mouse and human transgene) levels in mouse serum at 6 months of age. Graph represents the mean ± standard deviation from at least five mice per group. ***P < 0.001 for RBP4-Tg compared to WT by Student's t-test. (B) Quantification of bis-retinoid A2E in eyecups from 9-month-old mice. Values are means ± SEM from at least three samples (one sample consists of four eyecups pooled from two mice) per group. ns, not significant; **P < 0.01 for RBP4-Tg compared to WT; ##P < 0.01 for dark-reared RBP4-Tg compared to RBP4-Tg reared on normal cyclic light by 1-way ANOVA with Tukey's post hoc test. Note that dark-reared RBP4-Tg mice have significantly less A2E than RBP4-Tg reared in normal cyclic light, confirming the dark-rearing was successful. (C, D) Scotopic ERG a-wave (C) and b-wave (D) amplitudes in mice aged 6 months.
Fenretinide can bind and activate retinoic acid receptors (RARs) to elicit off-target effects, whereas A1120 does not bind RARs. Similar to previous studies, we found no obvious signs of A1120-induced systemic toxicity, as mice treated with A1120 had normal weight and food consumption and no signs of lethargy. Therefore, although the A1120-treated RBP4-Tg mice maintained serum RBP4 levels at or above wild-type level (Fig. 3A), the remaining RBP4 in the serum of A1120-treated mice is likely bound to A1120 and therefore unable to deliver much retinol to the retinal pigment.
FIGURE 4. A1120 treatment severely reduces retinyl ester stores in the retina, impairs OKT, and results in loss of cone photoreceptors. (A) HPLC-based quantification of visual cycle retinoid isomers in eyes from mice aged 6 months and dark-adapted for 16 hours prior to euthanization. Values are mean ± standard deviation from at least three mice per group. ns, not significant; **P < 0.01 for any RBP4-Tg group compared to wild-type (WT), $P < 0.05$, $$$P < 0.001 for RBP4-Tg on A1120 diet compared to RBP4-Tg on standard diet, #P < 0.05, ###P < 0.001 for RBP4-KO compared to WT by 1-way ANOVA with Tukey’s post hoc test. Note that A1120 diet groups have severely reduced retinyl ester levels that are similar to RBP4-KO mice. (B, C) OKT response to changes in spatial frequency (B) and grating contrast (C) in mice aged 4 months. All OKT analyses were performed.
on at least five mice per group. Values are mean ± standard error of the mean; *P < 0.05 for RBP4-Tg on standard diet compared to WT; $$$P < 0.01, $$$$$P < 0.001 for RBP4-Tg on either A1120 diet compared to RBP4-Tg on standard diet by 1-way ANOVA with Tukey’s post hoc test. Note that the mice on A1120 diet have very significant and severe reduction in OKT responses compared to RBP4-Tg mice on standard diet. (D, E) Representative images of retinal paraffin sections from 6-month-old mice immunofluorescently labeled for cone S-opsin, cone M-opsin, and cone arrestin as indicated. DAPI counterstaining is shown in blue. Images were acquired at 20× magnification, and the scale bar indicates 50 μm. The images in panel D correspond to the superior (M-opsin rich) retina, and images in panel E were taken from the inferior (S-opsin rich) retina. Note that the A1120 diet groups clearly have less staining for both S- and M-opsins, as well as cone arrestin.

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Moreover, A1120-treated regeneration of visual chromophore to sustain vision.32–34

mechanisms underlying the loss of cones and OKT impairment in mice on A1120 diet is unclear, but may be related to the severe depletion of retinyl ester stores. The mechanisms underlying the loss of cones and OKT impairment in mice on A1120 diet is unclear, but may be related to the severe depletion of retinyl ester stores in the retina. Cones function in bright light, and have a higher requirement for fast regeneration of visual chromophore to sustain vision.32–34 Moreover, in absence of visual chromophore, cones degenerate rapidly.35–38 Interestingly, a recent study in zebrafish suggests that retinyl ester stores are especially important to supply visual chromophore and thereby sustain bright light-cone-mediated vision.39 Thus, we speculate that the loss of cones in A1120-treated mice may be an indirect result of the depletion of retinyl ester stores, although we cannot rule out the possibility that A1120 has distinct and specific cone toxicity.

While it is difficult to directly extrapolate mouse studies to humans, the finding that A1120 treatment results in loss of cone photoreceptors and severely reduces OKT responses, an indirect measurement of visual acuity in rodents, suggests that future studies or plans to use A1120 as a therapeutic in humans should be approached with caution and attempt to identify the minimal dosing that may provide therapeutic benefit without eliciting extreme retinoid depletion, cone toxicity, or other adverse effects. The doses of A1120 used in this study were determined empirically to identify the necessary dosage to reduce serum RBP4 levels in RBP4-Tg mice to near wild-type levels. Since RBP4-Tg mice have an 8- to 10-fold elevation of serum RBP4 levels (Figs. 2A, 3A), and most clinical studies have found only a 2- to 5-fold elevation in serum RBP4 levels in humans with obesity,10,11 insulin resistance,10,15 and type 2 diabetes,11,15 it is likely that a lower dose of A1120 could be effective to lower serum RBP4 levels without causing adverse effects in humans.

Acknowledgments

The authors thank Mark Dittmar and the staff at the Dean McGee Eye Institute for assisting with establishing and maintaining a room in the animal research facility for dark-rearing mice, and Loredana Quadro, PhD, who kindly provided the RBP4-Tg and RBP4-KO mice. The authors also thank Konstantin Petrukhin, PhD, for providing A1120 for preliminary studies related to this manuscript. Supported by an institutional development award (IDEA) from the National Institute of General Medical Sciences of the National Institutes of Health under grant number P20GM104934 (KMF received funding as a promising junior investigator on this grant), and a bridge grant from the Presbyterian Health Foundation (KMF).

Disclosure: M. Du, None; E. Phelps, None; M.J. Balangue, None; A. Dockins, None; G. Moiseyev, None; Y. Shin, None; S. Kane, None; L. Otalora, None; J.-X. Ma, None; R. Farjo, None; K.M. Farjo, None

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