Absence of Sigma 1 Receptor Accelerates Photoreceptor Cell Death in a Murine Model of Retinitis Pigmentosa

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Submitted: March 28, 2017
Accepted: July 31, 2017
Citation: Wang J, Saul A, Cui X, Roon P, Smith SB. Absence of sigma 1 receptor accelerates photoreceptor cell death in a murine model of retinitis pigmentosa. Invest Ophthalmol Vis Sci. 2017;58:4545–4558. DOI:10.1167/iovs.17-21947

PURPOSE. Sigma 1 Receptor (Sig1R) is a novel therapeutic target in neurodegenerative diseases, including retinal disease. Sig1R−/− mice have late-onset retinal degeneration with ganglion cell loss under stress. Whether Sig1R plays a role in maintaining other retinal neurons is unknown, but was investigated here using rd10 mice, a model of severe photoreceptor degeneration.

METHODS. Wild-type, rd10, and rd10/Sig1R−/− mice were subjected to ERG and spectral-domain optical coherence tomography (SD-OCT) to assess visual function/structure in situ. Retinas imaged microscopically were subjected to morphometric analysis, immunodetection of cones, and analysis of gliosis. Oxidative and endoplasmic reticulum (ER) stress was evaluated at mRNA/protein levels.

RESULTS. Photopic ERG responses were reduced significantly in rd10/Sig1R−/− versus rd10 mice at P28 (31 ± 6 vs. 56 ± 7 µV), indicating accelerated cone loss when Sig1R was absent. At P28, SD-OCT revealed reduced retinal thickness in rd10/Sig1R−/− mice (60% of WT) versus rd10 (80% of WT). Morphometric analysis disclosed profound photoreceptor nuclei loss in rd10/Sig1R−/− versus rd10 mice. rd10/Sig1R−/− mice had 55% and 60% fewer photoreceptors, respectively, at P28 and P35, than rd10. Peanut agglutinin cone labeling decreased significantly; gliosis increased significantly in rd10/Sig1R−/− versus rd10 mice. At P21, NRF2 levels increased in rd10/Sig1R−/− versus rd10 mice and downstream antioxidants increased indicating oxidative stress. At P28, ER stress genes/proteins, especially XBP1, a potent transcriptional activator of the unfolded protein response and CHOP, a proapoptotic transcription factor, increased significantly in rd10/Sig1R−/− mice versus rd10.

CONCLUSIONS. Photoreceptor cell degeneration accelerates and cone function diminishes much earlier in rd10/Sig1R−/− than rd10 mice emphasizing the importance of Sig1R as a modulator of retinal cell survival.

Keywords: rd10 mouse, retinal neuroprotection, ERG, retinal degeneration, rods, cones

The major cause of untreatable blindness worldwide is retinal degenerative disease, most often due to death of photoreceptor or ganglion cells (RGCs).1 Retinitis pigmentosa (RP), a photoreceptor cell (PRC) degenerative disease, affects 1:3000 to 5000 people.2 Initially, rod PRCs are lost compromising vision in dim light (nyctalopia); slow, insidious loss of the visual field eventually leads to “tunnel vision.” Assessment of visual function by ERG reveals an extinguished scotopic (dark-adapted) response reflecting rod dysfunction. Subsequent cone loss, reflected as a decline of visual acuity, decreased vision in bright light, and diminished photopic ERG, is the most debilitating consequence of RP.2–4 If strategies can be developed to preserve cone function, even when rods are lost, the therapeutic impact on this devastating disease would be enormous.

RP is caused by more than 3000 mutations in more than 50 different genes.5 Given its heterogeneity, developing treatments for RP aimed at common disease mechanisms may be more successful than targeting specific genetic defects. Useful in this endeavor is the availability of models of RP, including the Pde6b0/0/J (rd10) mouse. Rd10 mice carry a spontaneous missense point mutation in exon 13 of the beta-subunit of rod cyclic guanosine monophosphate (cGMP) phosphodiesterase (β-PDE) gene.6–8 Mice lose rod PRCs beginning at postnatal day 18 (P18), the rod cell loss peaks at P25. Cone cell death occurs in this model. By P55 most cones are lost and the cone function is minimal.8

We recently investigated the consequences of activating the sigma 1 receptor (Sig1R) in attenuating cone cell loss in the rd10 mouse.9 Sig1R is a 25.3-kDa transmembrane receptor protein. Unlike many transmembrane receptors belonging to large, extensively studied families (e.g., G-protein-coupled receptors, ligand-gated ion channels), Sig1R is an evolutionary isolate with no discernible similarity to other proteins. Its recently published crystal structure in humans reveals a trimeric architecture with a single transmembrane domain in each protomer.10 Sig1R, a putative molecular chaperone,11 is an enigmatic protein whose precise physiological function is unknown. It is emerging as a unique pluripotent modulator of cell survival that interacts with many structurally diverse proteins.12–14 Mutations of Sig1R are implicated in human neurodegenerative diseases, including amyotrophic lateral...
Sigma 1 Receptor and Photoreceptor Cell Death

Electroretinogram

ERGs were obtained from dark-adapted mice anesthetized with isoflurane. Silver-coated nylon fibers joined to flexible wires were carefully placed on the cornea, and a drop of hypromellose coated the eye and provided improved electrical contact. Optic fibers of 1 mm diameter were positioned just in front of the pupils. A 5500° white light-emitting diode provided highly controllable illumination that was led to the eyes through the optic fibers. Experiments consisted of a series of tests with 5-ms flashes of increasing luminance, followed by photopic testing with 5-ms flashes above a pedestal, as well as other photopic stimuli that included a “natural” noise stimulus. The natural noise was a slowly varying luminance time series with amplitude inversely proportional to temporal frequency, termed the pseudorandom noise test. Data were averaged across the two eyes for each animal, then averages were computed for each group across the animals. Kernels were computed from the responses to the natural noise stimulus by correlating the responses with the stimuli.

Spectral-Domain Optical Coherence Tomography (SD-OCT)

The integrity of the retina was assessed in vivo using SD-OCT. Mice were anesthetized using a rodent anesthesia cocktail containing ketamine 100 mg/mL, xylazine 12 mg/mL (Sigma-Aldrich Corp., St. Louis, MO, USA). Pupils were dilated with 1% tropicamide (Bausch & Lomb, Tampa, FL, USA) followed by application of GenTeal Lubricant Eye Gel (Alcon, Ft. Worth, TX, USA). Systane lubricant eye drops (Alcon) were applied throughout the procedure to keep the cornea moist. SD-OCT images were obtained using the Bioptigen Spectral-Domain Ophthalmic Imaging System (Envisu R2200; Bioptigen, Morrisville, NC, USA). Imaging included averaged single B scan and volume intensity scans (VIP) with images centered on the optic nerve head. Postimaging analysis included auto segmentation report analysis and manual assessment of all retinal layers using InVivoVue Diver 2.4 software (Bioptigen). The OCT data from rd10 mice younger than P21 could be processed using auto-segmentation report analysis; however, OCT data from rd10 mice older than P21 required manual segmentation analysis. We measured total retinal thickness (TRT), thickness of nerve fiber layer thickness, inner plexiform layer (IPL), inner nuclear layer (INL), outer plexiform layer (OPL), ONL, inner/outer segment thickness, and RPE thickness. Each layer thickness was plotted separately, and the data for a given retinal layer in each group were averaged.

Histologic Processing of Tissue, Microscopic Evaluation, and Morphometric Analysis

Eyes, enucleated from euthanized mice, were prepared for cryosectioning or embedding in JB-4 methacrylate (Electron Microscopy Sciences, Hatfield, PA, USA). For cryosections,
eyes were flash frozen in liquid nitrogen and embedded in optimal cutting temperature compound (Tissue-Tek, Sakura Finetek, Torrance, CA, USA); 10-μm-thick cryosections were fixed 10 minutes in 4% paraformaldehyde (4% PFA), and blocked with 10% goat serum in 0.1% Triton X-100/PBS for 1 hour at room temperature. For plastic embedding, eyes were immersion-fixed in 2% paraformaldehyde/2% glutaraldehyde in 0.1M cacodylate buffer and processed for JB-4 embedding. Sections were stained with hematoxylin-cosin (H&E), retinal images captured using an Axiosplan-2 microscope equipped with a high-resolution camera, and processed using Zeiss Axiovision software (version 4.7; Carl Zeiss, Oberkochen, Germany). Retina sections were scanned first for gross disruption followed by comprehensive morphometric evaluation. Retinal thickness; thickness of INL, ONL, IPL, OPL, and inner/outer segments; and number of RGCs/100 μm retinal length were determined in six images captured temporal/ nasal to optic nerve, yielding data for central, midperipheral, and peripheral retina.

Immunofluorescence Studies in Retinal Cryosections and Flatmounted Retinas

Retinal cryosections were incubated with primary antibodies (anti-ccone, anti-glial fibrillary acidic protein (GFAP) or FITC-conjugated PNA followed by incubation with secondary antibodies (Supplementary Table S2). Oxidative stress was detected in retinal cryosections using chloromethyl derivative of 2′,7′-dichlorodihydrofluorescein diacetate (CM-H2DCFDA) (C6827; Molecular Probes/Thermo Scientific, Eugene, OR, USA) following the manufacturer’s protocol and quantified. RNA (2 μg) was reverse-transcribed using the iScript Synthesis Kit (BioRad Laboratories, Hercules, CA, USA). cDNAs were amplified for 40 cycles by using SsoAdvanced SYBR Green Supermix (BioRad Laboratories, Hercules, CA, USA). Gene expression levels were calculated by comparison of Ct values (delta-delta Ct). Protein was extracted from neural retina and subjected to SDS-PAGE; nitrocellulose membranes, to which the proteins had been transferred, were incubated with primary antibodies (Supplementary Table S2). Immunoblotting was performed to assess oxidative stress–related proteins (NRF2, KEAP1, SOD1, Catalase, NQO1, HMOX1) and ER stress–related proteins (IRE1α, XBP1, ATF4, CHOP, BIP/GRP78, PERK, IRE1α). Proteins were visualized using the SuperSignal West Pico Chemiluminescent Substrate detection system (Pierce Bio-technology, Waltham, MA, USA). Band densities were quantified using Image J 1.48v software.

Statistical Analysis

Statistical analysis was conducted using the GraphPad Prism analytical program (LaJolla, CA, USA), or for the ERG results, Igor Pro (Lake Oswego, OR, USA). Significance was established as P < 0.05. Data were analyzed by 1-way ANOVA for studies comparing one parameter among the three mouse groups or 2-way ANOVA (factors: mouse group and retinal region measured; mouse group and gene expression). We followed the recommendations for appropriate post hoc testing, which included Holm-Bonferroni, Tukey’s, and Newman-Keul’s Multiple Comparison Tests. Graphic representation of data significance was depicted as *P < 0.05; **P < 0.01; ***P < 0.001.

Results

Sig1R Deletion Compromises Photoreceptor Function in rd10 Mice

Scotopic ERGs performed on WT mice at P28 showed predictably robust responses (Fig. 1A) with b-wave amplitudes of 1000 μV at higher luminance intensities; rd10 mice had reduced responses averaging less than 200μV (Fig. 1B). There was significantly less rod responsiveness (<100 μV) in rd10/Sig1R+/− mice compared with rd10 mice at P28 (Fig. 1C). Cone function of WT mice was robust at P28 (Fig. 2A), with b-wave amplitudes greater than 100 μV as light intensity increased. rd10 mice showed detectable cone activity (approximately 40 μV) (Fig. 2B), whereas cone responses in P28 rd10/Sig1R+/− mice were reduced significantly compared with rd10 mice (approximately 20 μV) (Fig. 2C). P28 cone responses were evaluated using the pseudorandom luminance noise test (Figs. 2D, 2E). rd10 mice responded with approximately half-WT levels, whereas rd10/Sig1R+/− mouse responses were reduced dramatically compared with rd10 mice (Figs. 2D, 2E). These functional studies demonstrate accelerated PRC dysfunction, particularly cones, in rd10 mice lacking Sig1R.

Sig1R Deletion Accelerates Retinal Cell Loss in rd10 Mice

Consequences of Sig1R deletion on retinal structure in rd10 mice in vivo, monitored by SD-OCT, showed that over the period of study (P21–P42), TRT of WT mice averaged approximately 250 μm (Figs. 3A–D). In rd10 mice (P21), TRT was 80% that of WT (approximately 200 μm), whereas in rd10/Sig1R+/− mice, it was 60% that of WT (approximately 150 μm). TRT in rd10/Sig1R+/− mice was significantly less than rd10 mice through P35 (Figs. 3E–G), suggesting accelerated retinal degeneration in mice lacking Sig1R. Only at P42 was the TRT equivalent between rd10 and rd10/Sig1R+/− mice (Fig. 3H). The decrease in rd10 TRT by P42 is consistent with earlier reports.46 ONL thickness (ONL-T) measured by SD-OCT in WT mice ranged from approximately 65 to 85 μm over the period...
analyzed. rd10 mice had significantly reduced ONL-T of approximately 40 to 60 μm at P21; ONL-T diminished further in rd10/Sig1R−/− mice to only approximately 20 μm (Fig. 3I). Over the time course studied, P28, P35, P42, the rd10 ONL-T decreased from approximately 12 to approximately 7 μm, respectively (Figs. 3J-1). Decreased ONL-T accelerated dramatically in rd10/Sig1R−/− mice (approximately 5 μm at P28 and P35; only approximately 2 μm by P42 [Figs. 3J-L]). The inner/outer segments typically measure approximately 15 μm in WT mice and approximately 12 μm in rd10 (Fig. 3M). The thickness was reduced significantly in rd10/Sig1R−/− mice versus rd10 at P21, P28, and P35 (Figs. 3N-P). It has been reported by others that as the PRC loss becomes severe in rd10 mice (i.e., after P35 when there is less than one row of nuclei), the remaining retina may separate from the underlying RPE.7–9 An OCT analysis of rd10 mice reported by Hasegawa and colleagues16 noted approximately 30% of mice demonstrated this phenomenon. We observed a similar trend in rd10 mice by P35, whereas we observed this earlier (beginning at P28) in rd10/Sig1R−/− mice. Note that the data shown in Figures 3E-T represent 25 individual points within the retina where measurements are made. The software provided by the manufacturer reports data as a 5 × 5 grid. The 25 separate points (with the optic nerve head in the center #13) are depicted in Figure 3U.

The OPL is composed of synapses between PRCs and INL cells. It is approximately 10-μm thick in WT mice (Fig. 3Q). rd10 mice maintain an OPL similar to WT through P28, with gradual reduction by P35 (Figs. 3R-T); only at P42 is OPL reduced to 4 μm. In rd10/Sig1R−/− mice, OPL thickness decreased dramatically as early as P28 to approximately 5 μm (Fig. 3R), suggesting significantly diminished input to neurons within the INL.

Histologic Assessment Confirms Accelerated PRC Loss in rd10/Sig1R−/− Retina

WT, rd10, and rd10/Sig1R−/− retinas (P15-P42) were evaluated microscopically (Figs. 4A-G) and subjected to systematic morphometric analysis (Figs. 4H-Y). At P15, there was little difference in TRT of WT versus rd10 or rd10/Sig1R−/− mice (Fig. 4A). By P18, however, significant differences emerged, which were detectable morphometrically. rd10 mouse TRT was reduced compared with WT as early as P18 and thickness decreased gradually with age (Figs. 4H-M). rd10/Sig1R−/− mice showed pronounced TRT reduction, which differed significantly from rd10 mice at P21 to P42, confirming SD-OCT results (Fig. 3). ONL-T decreased in rd10 mice compared with WT by P18 (Fig. 4N), but was more pronounced in rd10/Sig1R−/− mice beginning at P21 (Fig. 4O). Indeed, from P21 through the oldest age examined (P42) ONL-T in rd10/Sig1R−/− mice was reduced significantly compared with rd10 mice (Figs. 4P-S).

WT retinas have approximately 10 to 12 rows of PRC nuclei (Figs. 4A-G). rd10 mice had 11 to 12 rows through P18, as did rd10/Sig1R−/− mice (Figs. 4A, 4B). Beginning at P21, there was a rapid decline in rows of nuclei in rd10 mice: P21, approximately seven to eight rows; P24, approximately five to six rows; P28, approximately three to four rows; P35, three to four rows; P42, one to two rows. The loss of PRC rows was more pronounced in rd10/Sig1R−/− mice: P21, six to seven rows; P24, three to four rows; P28, approximately one row. Beyond P28, PRC loss was so severe in rd10/Sig1R−/− retinas that it was not possible to count rows of cells; thus, we counted PRCs per 225-μm retinal length (field of view of ×20 microscope objective). PRC number in P28 rd10/Sig1R−/− retinas averaged 80.5 ± 10.3, which was approximately 35% less than rd10 retinas (125 ± 20.2). At P35, PRC number in rd10/Sig1R−/− retinas averaged 41.3 ± 13.9, which was...
approximately 60% less than rd10 retinas (107.1 ± 8.6). Clearly, PRC loss accelerates markedly in rd10 mice in the absence of Sig1R.

OPL-T was similar between WT, rd10, and rd10/Sig1R/C0/C0 mice at P18 and P21 (Figs. 4T, 4U); however, differences in this synaptic layer were detectable by P24; OPL-T was significantly less in rd10/Sig1R/C0/C0 mice compared with rd10 mice through P35 (Figs. 4V–Y). Despite the accelerated loss of outer retinal layers (ONL, OPL) there was no change in numbers of cells in the ganglion cell layer in rd10 or rd10/Sig1R/C0/C0 retinas over the period studied (data not shown).

Sig1R Deletion Accelerates Cone PRC Death in rd10 Mice

The genetic mutation in rd10 mice is specific for rod cGMP-PDE; however, cones are lost subsequently with age.5–8 We used FITC-PNA labeling to quantify cones in retinas of WT, rd10, and rd10/Sig1R/C0/C0 mice at P35. In WT mice, PNA labeling is robust in inner/outer segments (Fig. 5A); it is diminished in rd10 mice (Fig. 5B), and it is barely detectable in rd10/Sig1R/C0/C0 mice (Fig. 5C). Quantification of fluorescence intensity confirmed accelerated cone loss in rd10/Sig1R/C0/C0 mice (Fig. 5D). Additionally, retinal flatmounts optically sectioned by laser-scanning confocal microscopy to detect cone PRCs (Figs. 5E–G) showed fewer cones in rd10/Sig1R/C0/C0 mice compared with rd10 or WT mice (Fig. 5H).

Sig1R Deletion Accelerates Gliosis in rd10 Mice

Increased levels of GFAP, reflecting reactive gliosis in retina, is a sensitive indicator of retinal stress47 and has been reported in rd10 retina9,48,49. In WT, GFAP was restricted to the innermost retina reflecting astrocyte labeling (Fig. 6A). Retinas of rd10 mice showed distinct radial labeling consistent with activation of Müller glial cells (Fig. 6B). Much more intense
radial GFAP labeling was observed in rd10/Sig1R−/− retinas (Fig. 6C). Quantification of fluorescence intensity confirmed accelerated gliosis in rd10/Sig1R−/− retinas versus rd10 (Fig. 6D).

Microglia, resident retinal immune cells, are often reactive in degenerative and inflammatory retinal diseases, including RP. Microglial activation has been reported in rd10 mice. When activated, microglia secrete neurotoxic factors, including reactive oxygen and nitrogen species. To detect microglial activation in WT, rd10, and rd10/Sig1R−/− mice, flatmounted retinal preparations were subjected to Iba-1 labeling, which was minimal in WT (Fig. 6E). It increased significantly in rd10 retinas (Fig. 6F), but was greater still in rd10/Sig1R−/− retinas (Fig. 6G). The ramified appearance of Iba-1 labeled microglia in rd10/Sig1R−/− retinas (Fig. 6G) was more intense than observed in rd10 retinas (Fig. 6F), consistent with a highly activated state. Data are quantified in Figure 6H.

**Sig1R Deletion Increases Oxidative and ER Stress in rd10 Mice**

A pathogenic feature common in retinal disease is oxidative stress. Rod PRCs are prime oxygen consumers in retina. When they die, as in RP, inner retinal capillaries undergo atrophy. However, choroidal vessels supplying the outer retina with nutrients and oxygen do not autoregulate, thus oxygen from this vascular source is unchecked leading to a hyperoxic retinal environment. Oxidative damage is implicated in PRC death in rd10 mice. We evaluated oxidative stress in mutant mice at P21 because PRC loss was significantly greater at this age in rd10/Sig1R−/− versus rd10 mice (Figs. 1–4). We subjected retinal cryosections to CM-H2DCFDA, which fluoresces green in the presence of reactive oxygen species. Minimal fluorescence was detected in WT retinas; a modest level of green fluorescence was noticeable in P21 rd10 mice, whereas a stronger green fluorescence was observed in rd10/Sig1R−/− mice (Fig. 7A). A common cellular response to oxidative stress

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**Figure 3.** SD-OCT assessment. (A–D) Representative SD-OCT data obtained from WT mice, rd10 mice, and rd10/Sig1R−/− mice at P21 (A), P28 (B), P35 (C), and P42 (D). (E–T) Data for segmentation analysis for TRT at P21, P28, P35, and P42 (E–H), for ONL thickness at P21 to P42 (I–L), for IS/OS thickness at P21 to P42 (M–P), and for OPL thickness at P21 to P42 (Q–T). (U) The template (5 × 5 grid) for the OCT measurements. It represents the 25 points within the retina where retinal thickness is measured. Data are the mean ± SEM of analyses in 4 to 10 mice per group at each age. *P < 0.01, **P < 0.001. Note: For the OCT analyses, the x-axis represents the 25 points shown in (U), with point #13 representing the optic nerve, where the thickness is always zero.
is upregulation of Nrf2, which encodes NRF2 (nuclear factor erythroid 2-related factor 2), a molecule that regulates transcription of more than 500 antioxidant/cytoprotective genes.\textsuperscript{56,57} In the absence of overt stress, NRF2 is retained in cytoplasm by KEAP1 (kelch-like ECH-associated protein 1). Under cellular stress, KEAP1 releases NRF2, which translocates to the nucleus to activate ‘‘antioxidant response elements’’ of genes that encode cell defense proteins/enzymes. Under such situations, levels of NRF2 can increase, as has been reported in rd10 mice by age P42 when PRC loss is considerable.\textsuperscript{9} We examined levels of Nrf2 and Keap1 at P21. There was no increase in Nef2 or Keapf1 expression in rd10 mice compared with WT, but there was a significant increase in Nef2 in rd10/Sig1R\textsuperscript{−/−} mice (Fig. 7B). NRF2 protein levels increased significantly in rd10 retinas, but were greater still in rd10/Sig1R\textsuperscript{−/−} retinas (Figs. 7C, 7D). Expression of several NRF2-regulated antioxidant genes, including Sod1, Cat, Nqo1, Hmox1, and Gstt3, was greater in rd10/Sig1R\textsuperscript{−/−} compared with rd10 mice (Fig. 7E). Protein levels of SOD1, NQO1, and HMOX-1 were elevated in rd10/Sig1R\textsuperscript{−/−} versus rd10 retinas (Figs. 7F, 7G). The data indicate upregulation of the NRF2 antioxidant pathway in mutants lacking Sig1R compared with those expressing Sig1R.

Apoptotic death of PRCs is a feature of retinal degenerative diseases, including RP. C/EBP homologous 68 protein (CHOP) is a proapoptotic transcription factor activated in some models of RP.\textsuperscript{58} Expression of Chop mRNA in P21 rd10/Sig1R\textsuperscript{−/−} mice was greater than rd10 mice (Fig. 8A), which was accompanied by increased CHOP protein levels (approximately 5-fold increase in rd10/Sig1R\textsuperscript{−/−} mice versus WT compared with 2-fold increase in rd10 mice) (Figs. 8B, 8D).

Increased levels of CHOP and apoptosis of cells are characteristic of the unfolded protein response (UPR) in which misfolded proteins are retained in the endoplasmic reticulum.
FIGURE 4. Continued.
The initiation of UPR reflects altered levels of binding protein/glucose regulated protein 78 (BiP/GRP78), which in turn releases several ER integral membrane proteins: inositol requiring 1 (IRE1), pancreatic ER eIF2α kinase (PERK), and activating transcription factor 6 (ATF6). We examined BiP, IRE1, PERK, and ATF6 at the mRNA and protein levels in rd10 and rd10/Sig1R−/− retinas.

Although there was no change in gene expression of BiP/GRP78, at P21 in rd10 or rd10/Sig1R−/− mice compared with WT mice (Fig. 8A), there was a significant increase in BiP/GRP78 protein in rd10/Sig1R−/− retinas (4-fold greater than WT) (Figs. 8B, 8D). Expression of ATF6 was not changed also (at the gene and protein levels); however, there was a marked increase in Xbp1 and its encoded protein in rd10/Sig1R−/− retinas compared with rd10 or WT (Figs. 8A, 8B, 8D). Expression of IRE1α was unchanged also (at the gene and protein levels); however, there was a marked increase in Xbp1 and its encoded protein in rd10/Sig1R−/− retinas compared with rd10 or WT (Figs. 8A, 8B, 8D). XBP1, which is downstream of IRE1α, is a potent transcriptional activator of many UPR target genes, thus its increased expression in rd10/Sig1R−/− retinas versus rd10 is noteworthy. Expression of PERK was elevated significantly at the gene and protein levels in rd10/Sig1R−/− retinas compared with rd10 and WT retinas (Figs. 8A, 8C, 8D). Expression of ATF4, a protein downstream of PERK, whose activation can increase levels of chaperones and restore redox homeostasis, was also elevated slightly, albeit significantly, in rd10/Sig1R−/− retinas compared with rd10 or WT (Figs. 8A, 8B, 8D). Expression of ATF6 was not changed between rd10 and rd10/Sig1R−/− retinas (Fig. 8A). Owing to the putative role of Sig1R in chaperoning inositol phosphate 3 receptor 3 (IP3R3) at the ER/mitochondrion interface ensuring proper Ca2+ signaling, we examined IP3R3 expression; however, we detected no change in mRNA or protein levels in rd10 or rd10/Sig1R−/− retinas compared with WT (Figs. 8A, 8C, 8D).

DISCUSSION

Activation of Sig1R confers protective benefits in several models of neurodegenerative diseases, including retinal diseases. (+)-PTZ, a high-affinity Sig1R ligand, is the prototypical compound used to evaluate Sig1R activation. Remarkable cone rescue reported in the rd10 model of retinal degeneration requires the presence of Sig1R for (+)-PTZ to confer neuroprotection because, when absent, (+)-PTZ does not preserve cone function. Whether Sig1R can modulate rate...
FIGURE 6. Assessment of glial cell activation. (A–C) Immunodetection of GFAP (green) in retinal cryosections from WT (A), rd10 (B), and rd10/Sig1R<sup>−/−</sup> mice (C) at P35. Nuclei are labeled with DAPI (blue). (D) Quantification of fluorescence intensity in WT, rd10, and rd10/Sig1R<sup>−/−</sup> mice. Data are the mean ± SEM (three or four assays) from six to eight mice per group. *P < 0.05; ***P < 0.001 (Supplementary Table S1). (E–G) Retinal flatmounts immunolabeled with Iba-1 from WT (E), rd10 (F), and rd10/Sig1R<sup>−/−</sup> (G) mice. (H) Quantification of Iba-1 positive cells in retinal flatmounts. Data are the mean ± SEM (three or four assays) from six to eight mice per group. *P < 0.05; ***P < 0.001 (Supplementary Table S1). Calibration bars: (A–C): 100 μm, (E–G): 50 μm. Details about antibodies are provided in Supplementary Table S2.
or severity of rd10 PRC degeneration had not been addressed. The present work investigated this and provides evidence that rd10 PRC degeneration, especially cone dysfunction, is accelerated when Sig1R is absent.

Deletion of Sig1R (with no other known genetic mutations) does not have immediate deleterious consequences on retina. Rather, a late-onset RGC loss, with subtler dysfunction, manifests as mice age. Aside from RGC loss, the retina in Sig1R<–/– mice appears intact with no discernible loss of INL or ONL neurons. If Sig1R<–/– mice are subjected to additional stress, such as diabetes or optic nerve crush, RGC loss accelerates. To address whether Sig1R has a role in maintaining retinal neurons other than RGCs, we took advantage of an early-onset retinal pathology that predominately affects outer retina. The highly predictable PRC degeneration in rd10 mice allowed comprehensive assessment of effects of Sig1R deletion on rate/severity of outer retinal degeneration functionally and histologically. The analysis of rd10/Sig1R<–/– mice revealed accelerated PRC degeneration and loss of cone function much earlier than rd10/Sig1R<+/– mice. Interestingly, the RGC loss characteristic of Sig1R<–/– mice at approximately 9 to 12 months did not manifest at young ages (P15–P42) examined in rd10/Sig1R<–/– mice.

Functional tests used in this study included ERG and OCT. As expected, rod function (measured by scotopic ERG) was reduced markedly in rd10 mice compared with WT by P28. On the other hand, cone function was robust at this age (approximately 50% of WT). In P28 rd10/Sig1R<–/– mice, however, cone function was reduced to approximately 25% that of WT. The marked reduction in cone function in rd10/Sig1R<–/– mice was confirmed using natural noise stimuli in photopic ERG analysis. Assessment of retina using SD-OCT allowed measurements of retinal layer thicknesses in vivo. ONL-T at P21 in rd10 mice was approximately 75% of WT, whereas in rd10/Sig1R<–/– mice, it was approximately 25% of WT. This represents a markedly accelerated PRC loss in mutant mice lacking Sig1R. Functional retinal assessments were complemented by histologic and morphometric analyses. We observed accelerated PRC loss in rd10/Sig1R<–/– mice compared with rd10 mice as early as P21. When we used immunohistochemical methods to specifically label cone PRCs, we found significantly reduced labeling in rd10/Sig1R<–/– mice. We also detected increased gliosis in rd10/Sig1R<–/– mice in the form of increased GFAP labeling of Müller glial cells and increased Iba-1 levels indicative of increased microglial activity compared with rd10 mice. Taken collectively, the data indicate that in the absence of Sig1R, PRC degeneration and gliosis accelerate in this mutant model.

We acknowledge that the SD-OCT analysis showed separation of the neural retina from RPE at an earlier age (P28) in

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**Figure 7.** Assessment of oxidative stress–related genes and proteins. Immunodetection of CM-H2DCFDA (green fluorescence on reaction with reactive oxygen species) in retinal cryosections of (A) WT, rd10, and rd10/Sig1R<–/– at P21. Nuclei are labeled with DAPI (blue). Calibration bar: 50 μm. RNA was isolated from neural retinas and subjected to quantitative RFP PCR (qRFP PCR) analysis of (B) Nrf2, Keap1, Neural retinas harvested from WT, rd10, and rd10/Sig1R<–/– mice at P21 were used for isolation of protein. Representative immunoblots detecting (C) NRF2 and KEAP1. (D) Band densities of NRF2 and KEAP1 quantified densitometrically and expressed as fold change versus glyceraldehyde 3-phosphate dehydrogenase (GAPDH). RNA was isolated from neural retinas and subjected to qRFP PCR analysis of (E) Sod1, Catalase, Nqo1, Gpx1, Hmox1, and Gsat3. (F) Neural retinas harvested from WT, rd10, and rd10/Sig1R<–/– mice at P21 were used for isolation of protein. Representative immunoblots detecting SOD1, Catalase, NQO1, HMOX1, and β-Actin. (G) Band densities of SOD1, Catalase, NOQ1, HMOX1 quantified densitometrically and expressed as fold change versus β-Actin. Primer pairs for PCR studies are provided in Supplementary Table S3, and antibodies for immunodetection are provided in Supplementary Table S2. Data are the mean ± SEM of three assays from three different mice retinas in each group. *P < 0.05; **P < 0.01; ***P < 0.001.
rd10/Sig1R<sup>−/−</sup> mice compared with rd10 mice. There could be ischemia occurring in rd10/Sig1R<sup>−/−</sup> mice, which could severely affect PRC viability. The present study did not investigate retinal vasculature, but this would be an intriguing line of future work. It is noteworthy that the loss of PRCs in the ONL of the rd10/Sig1R<sup>−/−</sup> mice was significantly greater than rd10 mice at P18 and P21, ages that preceded detection of the neural retina-RPE separation. The decrease in inner segment/outer segment thickness is also of note, especially because the inner segment houses mitochondria and the absence of Sig1R may affect these organelles in the PRCs. Investigating this was beyond the scope of the present work, but warrants further study.

Retinal neuron death in degenerative diseases, such as RP, involves a variety of pathologic mechanisms, most notably oxidative stress<sup>2,3</sup> and ER stress<sup>58,62</sup>. As a putative molecular chaperone, Sig1R has been studied for its role in modulating these mechanisms; experimental evidence suggests that Sig1R activation attenuates both types of stress, and oxidative stress leads to activation of the NRF2-KEAP1 pathway.<sup>63</sup> We observed a modest increase in NRF2 levels in P21 rd10 mice compared with WT, but significantly higher NRF2 levels in age-matched rd10/Sig1R<sup>−/−</sup> mice. This was accompanied by increased levels of antioxidant proteins Sod1, Catalase, NQO1, and Hmx1 in rd10/Sig1R<sup>−/−</sup> mice compared with rd10 mice. The data suggest that if Sig1R is deficient, oxidative stress in an existing retinopathy increases. We find it intriguing and somewhat counterintuitive that NRF2 levels increase with concomitant increase of downstream antioxidants in the rd10/Sig1R<sup>−/−</sup> mutant mouse retina, because this pathway is considered a protective cellular mechanism to combat stress levels. The expectation would be that increased production of antioxidants would improve cellular survival. Perhaps when oxidative stress overwhelms the retina, as occurs in rd10/Sig1R<sup>−/−</sup> mice, the pathway remains upregulated. It is noteworthy that in an earlier study we also observed increased NRF2 levels and upregulation of antioxidants in rd10 mouse retinas, but administration of (+)-PTZ (i.e., activation of Sig1R) for many weeks gradually attenuated NRF2 and antioxidant gene expression, suggesting that oxidative stress had been reduced.<sup>3</sup> The data raise intriguing questions as to whether Sig1R has any role in regulating aspects of the NRF2 antioxidant pathway.

In our study, we also observed an increase in ER stress proteins BiP/GRP78, XBP1, and PERK in rd10/Sig1R<sup>−/−</sup> mice compared with rd10 mice. The most dramatic increase was in the ER-stress-related downstream protein XBP1, which is associated with ER-associated degradation of proteins.<sup>59</sup> In P21 rd10 mice, XBP1 was 2-fold greater than WT mice; however, it was 11-fold greater in rd10/Sig1R<sup>−/−</sup> mice. XBP1 is regulated by IRE1 and earlier reports demonstrate that Sig1R stabilizes IRE1 at the mitochondrion-associated ER membrane.<sup>13</sup> A major consequence of excessive ER stress is apoptosis, and CHOP is a key mediator of apoptosis.<sup>65</sup> As expected, because PRCs are beginning to die at P21, CHOP was elevated at the mRNA and protein levels in rd10 mice at P21; however, levels in rd10/Sig1R<sup>−/−</sup> mice were significantly greater than rd10 mice at this age. Thus, assessment of oxidative and ER stress reveals increased levels of both in the absence of Sig1R. Future studies could examine additional pathways that are likely involved in Sig1R-mediated cellular survival, including several proteins known to bind this molecular chaperone.<sup>14</sup>

In summary, there is considerable evidence supporting the role of Sig1R in maintaining ganglion cell function within retina.<sup>29,20,52,53,59,66,67</sup> The present work provides compelling evidence that Sig1R has a role in maintaining PRCs as well particularly in a preexisting PRC-degenerative condition. Retinal phenotype, especially cone survival and function, in an existing model of PRC degeneration worsened markedly in the absence of Sig1R. The findings provide strong in vivo data supporting the role of Sig1R as a modulator of retinal cell survival and may have far-reaching implications for Sig1R as a pathologic mediator in many organ systems.
Sigma 1 Receptor and Photoreceptor Cell Death

Acknowledgments

Supported by grants from the National Institutes of Health (R01 EY014560) and The Foundation Fighting Blindness (TA-NMT-0617-0721-AUG).

Disclosure: J. Wang, None; A. Saul, None; X. Cui, None; P. Roon, None; S.B. Smith, None

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