Low-Intensity Exercise in Mice Is Sufficient to Protect Retinal Function During Light-Induced Retinal Degeneration

Lukas M. Mees,1,2 Monica M. Coulter,2 Micah A. Chrenek,3 Cara T. Motz,2 Erica G. Landis,2,4 Jeffrey H. Boatright,2,3 and Machelle T. Pardue1,2

1Department of Biomedical Engineering, Georgia Institute of Technology, Atlanta, Georgia, United States
2Atlanta Veterans Administration Center for Visual and Neurocognitive Rehabilitation, Decatur, Georgia, United States
3Department of Ophthalmology, Emory University, Atlanta, Georgia, United States
4Neuroscience Program, Laney Graduate School, Emory University, Atlanta, Georgia, United States

Correspondence: Machelle T. Pardue, Atlanta VA Medical Center, Research Service (Oph151), 1670 Clairmont Road, Decatur, GA 30033, USA; machelle.pardue@bmc.gatech.edu.

Submitted: October 2, 2018
Accepted: February 7, 2019


PURPOSE. We previously reported that a specific treadmill running exercise regimen protects against light-induced retinal degeneration (LIRD) in mice. We hypothesized that this protective effect varies with running intensity. To test this, mice undergoing LIRD were run at different treadmill speeds and retinal function was assessed.

METHODS. BALB/c mice were assigned to LIRD groups at varying treadmill speeds—0, 5, 10, or 20 m/min labeled inactive, low, medium, and high, respectively—and compared with naive mice exposed to standard lighting (50 lux; naive). Following 2 weeks of exercise, a subset of mice were exposed to toxic light (10,000 lux; LIRD) for 4 hours. After 5 additional days of exercise, retinal function was assessed by ERG. Corticosterone levels in serum and cathepsin B (CTSB) protein levels in muscle, brain, serum, and retina were measured. The retinal gene expression of complement factor 1α (C1qa) and CTSB were measured.

RESULTS. The low+LIRD and medium+LIRD exercise groups had greater a- and b-wave ERG amplitudes when compared with the inactive+LIRD group (P < 0.02). The high+LIRD mice only differed from the inactive+LIRD mice in their dark-adapted b-waves. Serum corticosterone increased in the high+LIRD mice (P < 0.006). Retinal CTSB protein levels were higher in the low+LIRD versus high+LIRD mice (P < 0.004) but were otherwise unchanged. Exercise of any intensity decreased C1qa gene expression.

CONCLUSIONS. Faster running did not additionally protect against LIRD, but it did increase serum corticosterone, suggesting stress-induced limits to exercise benefits. Unexpectedly, exercise did not increase CTSB proteins levels in muscle or serum, suggesting that it may not mediate exercise effects. Our results have implications for the use of low-intensity exercise as a vision loss treatment.

Keywords: exercise, retinal degeneration, cathepsin B, neuroprotection

Exercise has been shown to enhance cognitive performance and protect against a variety of degenerative diseases within the central nervous system (CNS). In rodents, exercise improves performance on memory1 and learning tasks2 and stimulated neurogenesis.3 In humans, exercise improves memory,4,5 and learning5 and ameliorates cognitive dysfunction in patients with Alzheimer’s6 and Parkinson’s diseases.7,8 As part of the CNS, the retina is a target for exercise interventions, and emerging evidence shows that exercise could prevent and treat retinal degenerative diseases. Several studies suggest that increased physical activity is associated with reduced risk of development or progression of age-related macular degeneration, glaucoma, and diabetic retinopathy and that conversely reduced physical activity is associated with poorer outcomes in these disease groups (reviewed in Ref. 9). We find that increased physical activity is associated with greater self-reported visual function in patients with retinitis pigmentosa.9,10 Exercise preserves structure and function in animal models of several ocular diseases. We recently reported that treadmill exercise protects visual function in a rat model of streptozotocin (STZ)-induced diabetic retinopathy in pigmented Long-Evans rats,11 corroborating reports that treadmill exercise prevents retinal cell death in rats with diabetic retinopathy.12,13 Chrysotomou et al.14,15 report that swim exercise protects retinal ganglion cells against cell loss and dysfunction following acute injury from elevated intraocular pressure, a possible model of glaucoma. Finally, we find that voluntary running wheel exercise protects the retina in an inherited model of retinal degeneration, the pigmented Pde6brd10/rd10 (rd10) mouse,16 and that forced treadmill exercise protects against light-induced retinal degeneration (LIRD) in albino mice,17 a commonly used model of retinal degeneration.18

Although numerous studies in humans and animal models are directed at determining whether varying exercise dose or modality produces different effects on CNS function (reviewed in Refs. 19–21), the optimal exercise intensity for benefit to
The rat hippocampus.29–31 Rats exercised at low intensities to exercise and initiate signaling cascades continue to be explored. Myokines, small proteins that respond vary with intensity, lessening at lower running rates and potential mechanisms contributing to exercise's protection in responses, we aimed to further our understanding of the corticosterone, and C1qa. By combining the study of exercise the beneficial effects of exercise, we examined systemic and intensities to mice undergoing LIRD and measured retinal protection, we assigned varying forced treadmill exercise of these potential mediators.

Mechanisms underlying exercise-mediated retinal protection continue to be explored. Myokines, small proteins that respond within skeletal muscle to exercise and initiate signaling cascades throughout the body,27 could be partially responsible. Recently it was reported that one such myokine, cathepsin B (CTSB), increases in calf muscle, plasma, and the brain following exercise, stimulating neurotrophin production in the hippocampus that correlates with cognitive function.25 This suggests that exercise causes a systemic change in CTSB, which could travel to the brain and lead to neural benefits. Whether this relationship extends to the retina has not been studied.

In both humans and rodents, glucocorticoid levels, especially corticosterone, typically considered a stress hormone, rise during exercise.26–28 Glucocorticoids have been shown to influence neural function. When exposed to stress or exogenous corticosterone, neurotrophin mRNA and protein, including that of brain-derived neurotrophic factor, which we found in part mediates exercise-induced retinal protection.11,16,17 decreases in the rat hippocampus.29–31 Rats exercised at low intensities exhibit hippocampal neurogenesis, but this does not occur in rats exercising at a higher intensity that have a concurrent rise in corticosterone levels.27 It is possible that at lower intensities, exercise elicits a lower, therapeutic rise in glucocorticoids. Glucocorticoids possess anti-inflammatory properties22 and create a dose-dependent inhibitory effect on complement activation.23 Long-term exercise lowers systemic complement component 1qa (C1qa) levels and is associated with greater synaptic plasticity in the brain.34 It may be that low-intensity exercise is retinoprotective via modest increases in circulating glucocorticoid levels and decreased complement activation, but that beneficial effects decline at higher intensities of exercise as a result of noxious levels of stress-related glucocorticoids such as corticosterone. These relationships between exercise intensity, glucocorticoids, complement, and neural function have not been studied in the retina. Although secondary to the central question of whether protection varies with exercise intensity, our experimental design allowed for the correlative monitoring of these potential mediators.

To determine optimal levels of exercise for retinal function protection, we assigned varying forced treadmill exercise intensities to mice undergoing LIRD and measured retinal function using ERG. To determine the potential mechanisms of the beneficial effects of exercise, we examined systemic and retinal tissue for molecular changes, focusing on CTSB, corticosterone, and C1qa. By combining the study of exercise intensity and corresponding retinal functional and molecular responses, we aimed to further our understanding of the potential mechanisms contributing to exercise’s protection in degenerative disease.

**METHODS**

**Ethical Approval**

All procedures conformed to the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research and were approved by the Atlanta Veterans Administration Institutional Animal Care and Use Committee.

**Animals**

BALB/c male mice (8–10 weeks old; Charles River, Wilmington, MA, USA) were housed under a 12:12 light:dark cycle with ad libitum access to standard mouse chow.

**Exercise Regimen and Light Exposure**

In accordance with previous studies,17 the active mice ran 60 minutes per day between 10 AM and 12 PM on treadmills equipped with electric shock grating (Exer-3/6; Columbus Instruments, Columbus, OH, USA). The grating would inactivate if the mouse received 10 shocks in a single session. Before daily exercise, the mice were trained for 5 to 10 minutes at an intensity of 5 to 10 m/min for 2 consecutive days on the treadmill. The mice learned to maintain running within the first few days of running, receiving very few shocks after the first 1 to 2 days. Inactive mice were placed on static treadmills. Following 2 weeks of exercise, the mice were exposed to topical laboratory lighting (50 lux) or toxic light (10,000 lux) for 6 hours using an light emitting diode (LED) light panel (LED500A; Fancierstudio, Hayward, CA, USA) placed atop a standard mouse cage.35 A small subset (n = 10, with representation from all LIRD treated groups) received 40,000 lux for 1 hour and were not statistically different in retinal function from mice with the 10,000 lux treatment and so were included in the study (two-way repeated-measures ANOVA for a- and b-waves, P value > 0.25).

**Electroretinography (ERG)**

At 1 week after LIRD, retinal function was measured with a commercial ERG system (UTAS 3000; LKC Technologies,
Low-Intensity Exercise Protects Retinal Function

Low- to Medium-Intensity Exercise Protects Retinal Function From Light-Induced Retinal Degeneration

RESULTS

High-Intensity Exercise Elicits a Rise in Corticosterone

To evaluate the contribution of stress to the lack of functional protection in the high-LIRD mice, we evaluated serum corticosterone levels. Mice in the high-LIRD group had significantly higher serum corticosterone than the naive (2.7X higher, \( P < 0.01 \)), inactive-LIRD (2.9X higher, \( P < 0.01 \)), and low-LIRD mice (4.2X higher, \( P < 0.006 \); Fig. 3).
Exercise Does Not Alter Circulating and Muscle Levels of CTSB Protein

Although low- to medium-intensity exercise resulted in functional protection within the retina, there was no increase in CTSB protein levels within the calf muscle with exercise of any intensity (Fig. 4A), even when all exercised animals were compared against all sedentary animals (Fig. 4B). The CTSB protein levels were also unaltered in whole brain (Fig. 4C) and serum (Fig. 4D) with exercise.

In contrast, CTSB gene expression and protein levels were altered in the retina. CTSB mRNA was elevated in inactive þ LIRD mice, with ~1.3X greater expression than naïve (P < 0.001), low-intensity exercised (P < 0.003), and high-intensity exercised mice (P < 0.03; Fig. 4E). The CTSB protein levels in the retina of exercised mice were not greater than the levels in the inactive þ LIRD mice (Fig. 4F). However, the intensity of exercise produced a dose effect in retinal CTSB levels, with low þ LIRD mice having significantly higher levels when compared with high þ LIRD mice (1.6X higher, P < 0.004; Fig. 4F).

To determine if delayed elevations in CTSB protein occurred following the end of exercise, we exercised a small

**Figure 2.** Effect of exercise intensity on retinal function. Representative ERG waveforms are shown for maximum dark-adapted (DA) stimuli (A, 2.5 log cd s/m²) and flicker (E, 2.0 log cd s/m²). Quantified ERG amplitudes are depicted for dark-adapted a-wave (B), dark-adapted b-wave (C), light-adapted (LA) b-wave (D), and flicker (F). Data are depicted as mean ± SEM. Circles on (F) represent measurements for individual animals. Colored asterisks refer to the difference between the group they are closest to and the group of the referenced color. Amp, amplitude, div, division. *P < 0.026, **P < 0.005, ***P < 0.001.

**Figure 3.** High-intensity exercise increases serum corticosterone. Serum corticosterone was elevated in mice exercised at high intensity, but not low or medium intensity. Data are depicted as mean ± SEM. Circles represent measurements for individual animals. Colored asterisks refer to the difference between the group they are closest to and the group of the referenced color. *P < 0.05, **P < 0.01.
cohort of male BALB/c mice at 10 m/min for 1 or 3 weeks and killed them at 30 minutes and 1 and 3 hours after the final exercise session. There was no exercise-induced increase in CTSB at any time point in any tissue (Supplementary Fig. S1). CTSB Protein Levels Not Associated With Exercise-Induced Retinal Protection

To determine if systemic CTSB might underlie retinal function protection, we examined whether mice with the highest levels of calf muscle CTSB showed greater ERG amplitudes. Animals with a calf muscle CTSB level 10% higher than the max inactive+LIRD animal (1.90) were classified as “high CTSB” and compared with those below the threshold, labeled “low CTSB.” These two groups were statistically indistinguishable for dark-adapted b-wave \( (P = 0.45; \text{Fig. } 5A) \) as well as all other ERG parameters tested (Supplementary Fig. S2). Neither calf muscle nor retinal CTSB levels correlated with the dark-adapted b-wave amplitudes elicited with the brightest dark-adapted stimuli tested (calf muscle CTSB, \( P = 0.24, \text{Fig. } 5B \); retinal CTSB \( P = 0.62, \text{Fig. } 5C \)).

Complement C1qa Gene Expression Lower in Exercised Mice

Because complement factor levels increase during retinal degenerative diseases\(^{14,40}\) and exercise decreases systemic complement induction\(^{54}\) and C1q deposition in retinal ischemia, we hypothesized that exercise would decrease C1qa mRNA levels in the retina. As expected, retinal C1qa expression was elevated in the inactive+LIRD mice when compared with naive controls (6.1X higher, \( P < 0.001 \)). All exercise intensities decreased the expression of retinal C1qa when compared with inactive+LIRD mice (low+LIRD, 2.2X smaller, \( P < 0.001 \); med+LIRD, 2.2X smaller, \( P < 0.002 \); high+LIRD, 2X smaller, \( P < 0.002 \); Fig. 6). The high+LIRD expression level was slightly higher than the other exercise groups, reaching statistical difference when compared with naive mice (\( P < 0.04 \)).

DISCUSSION

Exercise shows promise as an intervention for retinal degenerative disease, but many questions remain about the nature of its protective effects. Consistent with previous studies\(^{12-14,16,17,41,42}\) we confirmed that exercise protects retinal function in a retinal degeneration model. We advanced these findings by demonstrating that higher intensity exercise may not provide more benefit to retinal function after LIRD, potentially because of the increased stress as reflected by increased circulating corticosterone levels. Instead, we found that lower intensity exercise did not alter corticosterone levels and protected retinal function. Furthermore, although not tested as causative, our results show that the beneficial effects of exercise on retinal function are accompanied by (1) local
retinal increases in CTSB protein but not circulating levels and (2) a decrease in retinal complement gene expression.

Across all ERG parameters, low- to medium-intensity exercise gave robust protection from LIRD, whereas high-intensity exercise did not (except for a small increase in dark-adapted b-wave amplitude). One possibility for reduced functional preservation in the high-LIRD mice is increased stress. Corticosterone, the major murine glucocorticoid released in response to stress, has been shown to inhibit neurogenesis at high exercise intensities. This relationship was confirmed in the current study, as the high-LIRD mice had a significant increase in serum corticosterone, but lacked functional protection.

Although the 10 m/min treadmill exercise regimens have previously been shown to protect against LIRD, it was not known if lower intensity exercise would be beneficial. One exciting application for this lower intensity but equally effective exercise treatment is for those suffering from age-related retinal degeneration. Although higher intensity exercise such as running would be challenging for a large portion of the older population affected by early retinal disease and other comorbidities, many would be able to engage in low-intensity exercise such as walking.

We were unable to replicate results reported by others that suggest exercise-induced benefit to neuronal function is mediated by CTSB released by skeletal muscle. In our study, exercise did not produce a significant increase in CTSB in muscle, brain, or serum. In addition, ERG amplitudes did not correlate with calf muscle CTSB levels; even mice with the highest levels of calf muscle CTSB were not found to have increased retinal function benefits. It is unlikely that CTSB elevations were delayed following exercise, as we did not observe any increase up to 3 hours following exercise. Collectively, these results do not support a role for systemic CTSB in exercise-mediated neural protection.

The dose-dependent relationship seen in the retinal CTSB protein levels with exercise intensity suggests that exercise may have a local effect on retina tissue. However, retinal CTSB protein levels did not correlate with ERG amplitudes (Fig. 4), and retinal CTSB gene expression was only elevated in inactive+LIRD mice (Fig. 5). Our results suggest that if CTSB influences the retina, it does so locally, and not through a systemic mechanism. Additional studies are needed to evaluate CTSB gene expression and protein in exercise and LIRD groups and determine the potential source of CTSB protein in the retina.

Exercise is sometimes considered a preconditioning stimulus. We may have detected elevated CTSB expression in inactive+LIRD animals because the tissue was still actively responding to injury when the mice were killed, whereas animals with exercise preconditioning were primed to handle the injury and would quickly return to homeostasis, as suggested for other potential mediators of light-induced stress responses. In support of this hypothesis, the inactive+LIRD animals had elevated retinal C1qa expression when compared with naïve mice, suggesting that the complement response in the retinas of sedentary animals was active a week after the injury. In comparison, the exercised mice had levels of retinal C1qa expression close to the levels observed in the naïve mice. This effect of treadmill running may generalize to other exercise modalities and other retinal damage models as it is reminiscent of outcomes reported in a retinal ganglion cell damage model, where the C1q deposition increase induced by acute elevation of intraocular pressure was prevented in mice that had undergone a swim exercise regimen. Measurements of the expression levels of these genes across time relative to light-induced injury are needed to more fully understand if a preconditioning effect is present in the retina in response to exercise.

In the current study, lower intensity exercise protected the retina from LIRD, whereas higher intensity exercise did not. Increased stress in mice undergoing higher intensity exercise may have diminished potential protection. No clear role for CTSB in functional protection was found. As true for more than 65 years in the wider field of exercise-induced CNS effects, further studies are needed to uncover the mechanism linking exercise with retinal neuroprotection. Low-intensity exercise...
was strengthened as a candidate for treating retinal degenerative disease in the current study, and its greater accessibility could make it an influential intervention.

**Acknowledgments**

Supported by Center for Visual and Neurocognitive Rehabilitation Pilot funds (Center Grant Number C924GC), Research Career Scientist Award RX001924 from the United States Department of Veterans Affairs Rehabilitation R&D Service; National Institutes of Health R01EY028859 and P30EY006560; the Abraham J. & Phyllis Katz Foundation; and an unrestricted grant to the Department of Ophthalmology at Emory University from Research to Prevent Blindness, Inc.

Disclosure: L.M. Mees, None; M.M. Coulter, None; M.A. Chrenek, None; C.T. Motz, None; E.G. Landis, None; J.H. Boatright, None; M.T. Pardue, None.

**References**


