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Inhibition of oxidative stress by coenzyme Q10 increases mitochondrial mass and improves bioenergetic function in optic nerve head astrocytes

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Oxidative stress contributes to dysfunction of glial cells in the optic nerve head (ONH). However, the biological basis of the precise functional role of mitochondria in this dysfunction is not fully understood. Coenzyme Q10 (CoQ₁₀), an essential cofactor of the electron transport chain and a potent antioxidant, acts by scavenging reactive oxygen species (ROS) for protecting neuronal cells against oxidative stress in many neurodegenerative diseases. Here, we tested whether hydrogen peroxide (100 μ M H₂O₂)-induced oxidative stress alters the mitochondrial network, oxidative phosphorylation (OXPHOS) complex (Cx) expression and bioenergetics, as well as whether CoQ₁₀ can ameliorate oxidative stress-mediated alterations in mitochondria of the ONH astrocytes *in vitro*. Oxidative stress triggered the activation of ONH astrocytes and the upregulation of superoxide dismutase 2 (SOD2) and heme oxygenase-1 (HO-1) protein expression in the ONH astrocytes. In contrast, CoQ₁₀ not only prevented activation of ONH astrocytes but also significantly decreased SOD2 and HO-1 protein expression in the ONH astrocytes against oxidative stress. Further, CoQ₁₀ prevented a significant loss of mitochondrial mass by increasing mitochondrial number and volume density and by preserving mitochondrial cristae structure, as well as promoted mitofilin and peroxisome-proliferator-activated receptor- γ coactivator-1 protein expression in the ONH astrocyte, suggesting an induction of mitochondrial biogenesis. Finally, oxidative stress triggered the upregulation of OXPHOS Cx protein expression, as well as reduction of cellular adenosine triphosphate (ATP) production and increase of ROS generation in the ONH astrocytes. However, CoQ₁₀ preserved OXPHOS protein expression and cellular ATP production, as well as decreased ROS generation in the ONH astrocytes. On the basis of these observations, we suggest that oxidative stress-mediated mitochondrial dysfunction or alteration may be an important pathophysiological mechanism in the dysfunction of ONH astrocytes. CoQ₁₀ may provide new therapeutic potentials and strategies for protecting ONH astrocytes against oxidative stress-mediated mitochondrial dysfunction or alteration in glaucoma and other optic neuropathies.

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Subject Category: Neuroscience

Impaired mitochondrial oxidative phosphorylation (OXPHOS) generates excessive reactive oxygen species (ROS), leading to mitochondrial damage, oxidative stress and apoptotic cell death.^{1,2} Increasing evidence demonstrates that oxidative stress links to mitochondrial dysfunction in glaucomatous neurodegeneration.^{2–5} A recent study reported that lamina cribrosa cells in the optic nerve head (ONH) from glaucomatous human patients showed increased ROS production, impaired mitochondrial function and elevated cytosolic Ca²⁺,³ suggesting that a cycle of oxidative stress, mitochondrial dysfunction and dysregulation of calcium homeostasis may

contribute to the pathogenesis of ONH degeneration in glaucoma.³ Although alteration of antioxidant enzymes has been implicated in glaucomatous ONH astrocytes,⁶ it remains unknown whether oxidative stress alters the mitochondrial network and triggers bioenergetic dysfunction in the ONH astrocytes.

Glaucoma is the leading cause of irreversible blindness and affects 70 million people worldwide.⁷ Although elevated intraocular pressure (IOP) is an important risk factor for ONH degeneration and retinal ganglion cell (RGC) death in glaucoma, lowering IOP is not always effective for preserving

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Keywords: oxidative stress; optic nerve head astrocytes; mitochondrial dysfunction; coenzyme Q10; glaucoma; OXPHOS complex

Abbreviations: ATP, adenosine triphosphate; BSA, bovine serum albumin; CoQ₁₀, coenzyme Q10; CM-H₂DCFDA, 5-(and-6)-chloromethyl-2',7'-dichlorodihydrofluorescein diacetate, acetyl ester; Cx, complex; DMEM, Dulbecco's modified Eagle's medium; DPBS, Dulbecco's phosphate-buffered saline; FBS, fetal bovine serum; GFAP, glial fibrillary acidic protein; H₂O₂, hydrogen peroxide; HO-1, heme oxygenase-1; IOP, intraocular pressure; MBP, myelin basic protein; MTT, 3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyl tetrazolium bromide; ONH, optic nerve head; OXPHOS, oxidative phosphorylation; PBST, 0.1% Tween-20 in PBS; PGC-1 α , peroxisome-proliferator-activated receptor- γ coactivator-1; RGC, retinal ganglion cell; ROS, reactive oxygen species; SA, surface area; SOD2, superoxide dismutase 2

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visual function in patients.⁷ Alterations in astrocytes have been implicated as important pathophysiological mechanisms in glaucomatous ONH degeneration.^{8–10} However, the biological basis of the precise functional role of ONH astrocytes in glaucomatous neurodegeneration is not fully understood.

Since the first evidence of impaired mitochondrial respiration-mediated mitochondrial dysfunction in patients with primary open-angle glaucoma,⁴ we have found that mitochondrial dysfunction is associated with ONH degeneration and RGC death in a mouse model of glaucoma,^{11–13} suggesting a distinct mitochondrial dysfunction-mediated degenerative pathway in glaucomatous neurodegeneration. Growing evidence indicates that glaucomatous damage, including elevated IOP, contributes to dysfunction of glial cells or loss of astrocytic processes in the ONH of rodent models of glaucoma.^{10,14} Regardless, the relationship between mitochondrial dysfunction and ONH astrocytes in glaucomatous neurodegeneration remain unknown.

Coenzyme Q10 (CoQ₁₀), an essential cofactor of the electron transport chain, acts by maintaining the mitochondrial membrane potential, supporting adenosine triphosphate (ATP) synthesis and inhibiting ROS generation, thus protecting neuronal cells against oxidative stress in neurodegenerative diseases.^{15–17} Of note, the levels of CoQ₁₀ in the human retina can decline by ~40% with age,¹⁸ raising the possibility that this decline of CoQ₁₀ may contribute to age-related ROS generation in glaucomatous ONH neurodegeneration. Previous studies demonstrated that CoQ₁₀ protects retinal cells against oxidative stress *in vitro* and *in vivo*, as well as prevents retinal damage induced by acute IOP elevation or excitotoxicity *in vivo*.^{19–22}

Here, we tested whether hydrogen peroxide (H₂O₂)-induced oxidative stress alters the mitochondrial network, bioenergetics and OXPHOS complex (Cx) expression, and whether CoQ₁₀ can ameliorate oxidative stress-mediated alterations in mitochondria of ONH astrocytes *in vitro*.

Results

CoQ₁₀ ameliorates oxidative stress in the ONH astrocytes.

Pure ONH astrocytes were generated from postnatal day 5 Sprague–Dawley rats using a modification of a previous protocol by Hernandez *et al*.²³ As shown in Figure 1, the cells migrated from cultured ONH tissues were purified by vigorous shaking and serum deprivation (Figure 1a). To confirm whether purified cells were astrocytes, we performed Western blot and immunocytochemical analyses using markers for astrocytes, microglial cells and oligodendrocytes. We found that the purified cells were positive for glial fibrillary acidic protein (GFAP), a marker for astrocytes, but were negative for Iba1, a marker for microglial cells, and myelin basic protein (MBP), a marker for oligodendrocytes (Figure 1b). In contrast, the protein extract from rat ONH tissues contained all four of markers. Immunocytochemistry showed a strong immunoreactivity for GFAP in cultured ONH astrocytes (Figure 1b), suggesting that the purified cells from ONH tissues were astrocytes.

As reduction of oxidative stress has been proposed to be protective against glaucomatous damage,^{24,25} we determined whether CoQ₁₀ treatment prevents oxidative stress-mediated

activation of ONH astrocytes *in vitro* using antibodies for GFAP, superoxide dismutase 2 (SOD2) and heme oxygenase-1 (HO-1). We observed that GFAP protein expression was significantly increased by 1.23 ± 0.10 -fold in the ONH astrocytes exposed to H₂O₂ (100 μ M) compared with control cells exposed to vehicle. In contrast, CoQ₁₀ significantly reduced GFAP protein expression by 0.97 ± 0.08 -fold in the ONH astrocytes exposed to H₂O₂ (Figure 2a). Intriguingly, we also found that SOD2 and HO-1 protein expression was significantly increased by 1.40 ± 0.13 - and 1.2 ± 0.14 -fold in the ONH astrocytes exposed to H₂O₂ compared with control cells, respectively. In contrast, CoQ₁₀ significantly reduced SOD2 and HO-1 protein expression by 0.63 ± 0.11 - and 0.63 ± 0.07 -fold in the ONH astrocytes exposed to H₂O₂, respectively (Figure 2a). To determine whether oxidative stress alters SOD2 distribution and expression in the ONH astrocytes, we performed immunocytochemistry in cultured ONH astrocytes using the antibody for SOD2. Consistently, we found that SOD2 immunoreactivity was present in the mitochondria of the ONH astrocytes. Moreover, we observed that ONH astrocytes exposed to H₂O₂ showed increase of SOD2 immunoreactivity in the mitochondria and cytoplasm compared with control cells. In contrast, CoQ₁₀ decreased SOD2 immunoreactivity in the ONH astrocytes exposed to H₂O₂ (Figure 2b). These results indicate that CoQ₁₀ prevents activation of ONH astrocytes by blocking oxidative stress.

CoQ₁₀ triggers mitochondrial biogenesis against oxidative stress.

To determine whether oxidative stress triggers alteration of the intracellular mitochondrial network in ONH astrocytes and whether CoQ₁₀ treatment inhibits this alteration in mitochondria against oxidative stress, the mitochondrial morphology of ONH astrocytes were assessed by MitoTracker Red (Invitrogen-Molecular Probes, Eugene, OR, USA) staining, a marker for mitochondria. Further, we quantified the alterations of mitochondrial number, length and volume density following exposure of H₂O₂ using transmission electron microscopy (TEM) analysis. Our results showed that control ONH astrocytes contained classic elongated tubular mitochondria. However, ONH astrocytes exposed to H₂O₂ contained small rounded mitochondria. Interestingly, ONH astrocytes pretreated with CoQ₁₀ and exposed to H₂O₂ showed a partial preservation of mitochondrial morphology compared with the ONH astrocytes exposed to H₂O₂ (Figure 3). Of note, representative 2D images from TEM showed that ONH astrocytes exposed to oxidative stress produced fewer mitochondria. In good agreement with this result, quantitative analyses importantly showed that the number of mitochondria, normalized to the total area occupied by somas in each image, was significantly decreased in the ONH astrocytes exposed to H₂O₂ ($0.15 \pm 0.01 \mu\text{m}^2$) compared with control ONH astrocytes ($0.52 \pm 0.07 \mu\text{m}^2$; $P < 0.001$; Figures 4a and b). In contrast, pretreatment of CoQ₁₀ increased mitochondrial numbers to a lesser extent (0.26 ± 0.03) compared with ONH astrocytes exposed to H₂O₂ ($P < 0.05$; Figure 4b). In addition, mitochondrial volume density, defined as the volume occupied by mitochondria divided by the volume occupied by the cytoplasm in terms of a percentage, was decreased in the ONH astrocytes exposed to H₂O₂ ($3.58 \pm 0.38\%$) compared

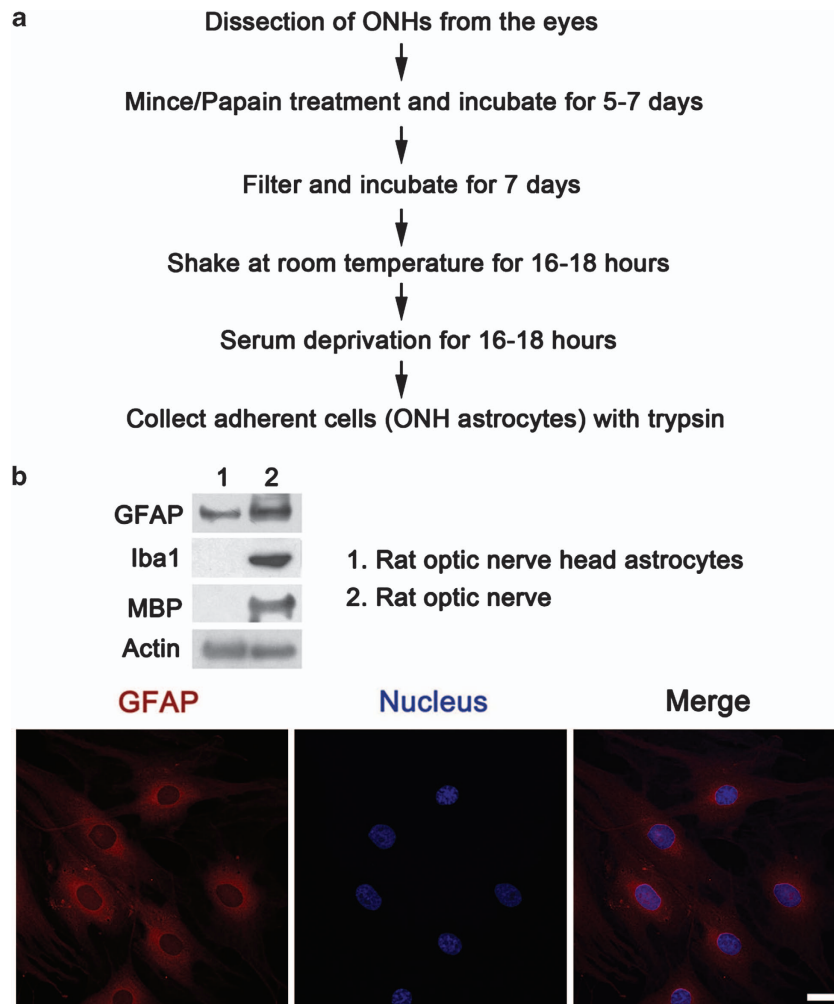


Figure 1 Characterization of cultured rat optic nerve head (ONH) astrocytes. (a) The diagram represents purification of ONH astrocytes from rats. (b) The protein extracts from ONH astrocytes were positive for GFAP, a marker for astrocytes but were negative for Iba1, a marker for microglial cells, and MBP, a maker for oligodendrocytes. The protein extract from rat optic nerve tissue was used for positive control. A representative image shows that GFAP immunoreactivity is present in the ONH astrocytes. GFAP, glial fibrillary acidic protein; MBP, myelin basic protein. Scale bar, 20 μ m

with control ONH astrocytes ($6.36 \pm 0.87\%$; $P < 0.01$; Figures 4a and b). In contrast, pretreatment of CoQ₁₀ significantly increased the mitochondrial volume density ($5.84 \pm 0.75\%$) compared with ONH astrocytes exposed to H₂O₂ ($P < 0.05$; Figure 4b). Interestingly, however, there was no difference in mitochondrial length among control, H₂O₂- and CoQ₁₀/H₂O₂-treated ONH astrocytes (Figures 4a and b), indicating that mitochondrial biogenesis by CoQ₁₀ did not come from increased mitochondrial fusion but rather by nascent mitochondria.

CoQ₁₀ promotes mitofilin and PGC-1 α protein expression against oxidative stress. The mitochondrial inner membrane protein mitofilin is critical for maintenance of mitochondrial cristae morphology and is reduced following oxidative stress.^{26,27} To determine whether H₂O₂-induced oxidative stress triggers loss of mitofilin protein expression in the ONH astrocytes and whether CoQ₁₀ treatment prevents this loss, we examined the protein expression level of mitofilin using western blot analysis. We found that oxidative

stress triggered a significant loss of mitofilin protein expression by 0.36 ± 0.04 -fold in the ONH astrocytes ($P < 0.01$; Figure 4c). In contrast, CoQ₁₀ significantly promoted mitofilin protein expression by 0.59 ± 0.02 -fold in the ONH astrocytes exposed to H₂O₂ compared with H₂O₂-treated ONH astrocytes ($P < 0.05$; Figure 4c). However, there was no difference of porin protein expression between H₂O₂ and CoQ₁₀/H₂O₂-treated ONH astrocytes (Figure 4c), suggesting that CoQ₁₀ could be protective in the mitochondria of ONH astrocytes by increasing the expression of mitofilin that in turn may protect mitochondrial cristae structure and ultimately OXPHOS capacity against oxidative stress. On the basis of increased mitochondrial mass by increasing mitofilin protein expression, we also determined whether CoQ₁₀ triggers mitochondrial biogenesis using the antibody for peroxisome-proliferator-activated receptor- γ coactivator-1 (PGC-1 α), a transcriptional coactivator and a mediator of mitochondrial biogenesis, in the ONH astrocytes exposed to H₂O₂. We found that oxidative stress significantly increased PGC-1 α protein expression by 1.34 ± 0.22 -fold in the ONH astrocytes

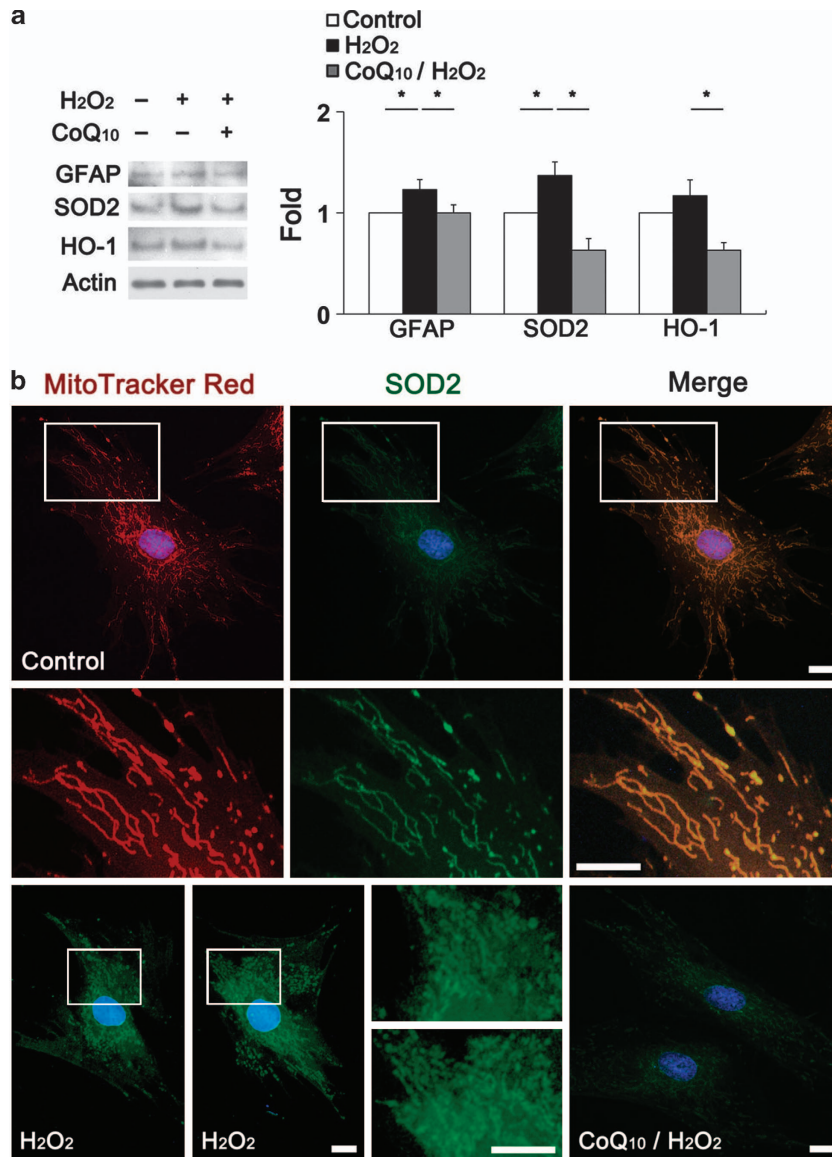


Figure 2 CoQ₁₀ ameliorates oxidative stress in ONH astrocytes. (a) GFAP, SOD2 and HO-1 protein expression were significantly increased in the ONH astrocytes exposed to H₂O₂ (100 μ M) compared with vehicle-treated control ONH astrocytes. In contrast, CoQ₁₀ significantly reduced GFAP, SOD2 and HO-1 protein expression compared with ONH astrocytes exposed to H₂O₂. Relative intensity of chemiluminescence for each protein band was normalized using actin. Values are mean \pm S.D. **P* < 0.05 compared with vehicle-treated control ONH astrocytes or H₂O₂-treated ONH astrocytes. (b) Representative images show that SOD2 immunoreactivity was present in mitochondria of the ONH astrocytes. Of note, SOD2 immunoreactivity was increased in the ONH astrocytes exposed to H₂O₂. However, CoQ₁₀ decreased SOD2 immunoreactivity in the ONH astrocytes exposed to H₂O₂. GFAP, glial fibrillary acidic protein; SOD2, superoxide dismutase 2; HO-1, heme oxygenase-1; CoQ₁₀, coenzyme Q10; H₂O₂, hydrogen peroxide. Scale bars, 10 μ m

(*P* < 0.05; Figure 4c). Of interest, CoQ₁₀ showed greater increase of PGC-1 α protein expression by 1.74 ± 0.40 -fold in the ONH astrocytes exposed to H₂O₂ (*P* < 0.05; Figure 4c), suggesting that CoQ₁₀ could also be protective in the ONH astrocytes by triggering mitochondrial biogenesis against oxidative stress.

To better visualize the cristae, we performed electron tomography, a technique that provides the highest resolution three-dimensional (3D) structure determination of mitochondria. We generated tomographic reconstructions of 15 control, 60 H₂O₂-exposed and 33 CoQ₁₀/H₂O₂-treated mitochondria and noticed that the cristae appeared dilated in the H₂O₂-exposed mitochondria (Figure 5). Measurements of

cristae widths in the mitochondrial volumes showed that control cristae were 32 ± 5 nm (mean \pm S.D.) across (membranes included), CoQ₁₀/H₂O₂-treated cristae were 31 ± 6 nm across, yet H₂O₂-exposed cristae were 48 ± 17 nm across, a value statistically different from control and CoQ₁₀/H₂O₂-treatment values (*P* < 0.001, Figure 5). The variation in cristae width was much greater in the H₂O₂-exposed mitochondria reflecting that not all the cristae were dilated. In comparison, the cristae widths in control and CoQ₁₀/H₂O₂-treated mitochondria were more uniform (Figure 5). The abnormal cristae associated with oxidative stress are consistent with our finding of reduced ATP production. To further determine cristae abundance, we also

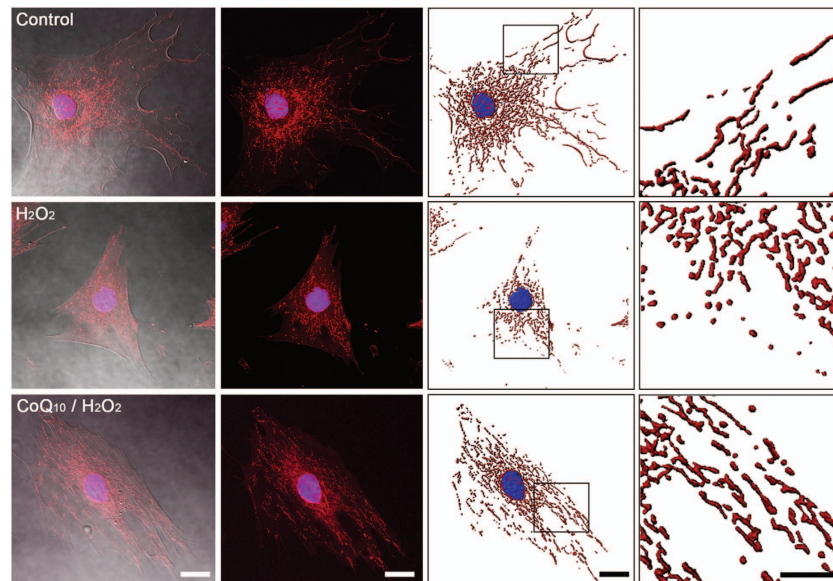


Figure 3 CoQ₁₀ partially preserves mitochondrial structure of ONH astrocytes against oxidative stress-induced mitochondrial fission. The mitochondria of ONH astrocytes were stained with MitoTracker Red. Control ONH astrocytes exposed to vehicle contained classic elongated tubular mitochondria. In contrast, ONH astrocytes exposed to H₂O₂ contained small rounded mitochondria. However, ONH astrocytes pretreated with CoQ₁₀ showed a partial preservation of mitochondrial morphology compared with the ONH astrocytes exposed to H₂O₂. CoQ₁₀, coenzyme Q10; H₂O₂, hydrogen peroxide. Scale bars, 10 μ m

performed measurement of mitochondrial cristae abundance. The parameter is cristae membrane surface area (SA) normalized to the outer membrane area, that is, cristae membrane SA divided by outer membrane SA that is dimensionless. Measurement of cristae abundance in the mitochondria showed that H₂O₂-exposed cristae significantly increased cristae abundance by 1.75 ± 0.09 ($n=5$, mean \pm S.E.M.) compared with control cristae abundance by 0.95 ± 0.26 ($n=5$; $P<0.05$, Figure 5). Pretreatment of CoQ₁₀ decreased cristae abundance by 1.43 ± 0.33 ($n=5$) in the ONH astrocytes exposed to H₂O₂; however, there was no statistical difference between H₂O₂ and CoQ₁₀/H₂O₂-treated ONH astrocytes (Figure 5).

CoQ₁₀ preserves OXPHOS Cx protein expression against oxidative stress. Pretreatment of CoQ₁₀ has been proposed to have a beneficial effect in the treatment of OXPHOS disorders.^{28–30} To determine whether H₂O₂-induced oxidative stress alters OXPHOS Cx protein expression and whether CoQ₁₀ preserves OXPHOS Cx protein expression in ONH astrocytes, we examined the protein expression level of OXPHOS Cxs using western blot analysis. As shown in Figure 6, H₂O₂-induced oxidative stress significantly increased OXPHOS Cx (Cx I and II) protein expression by 2.56 ± 0.08 - ($P<0.001$) and 1.93 ± 0.09 -fold ($P<0.01$) compared with control ONH astrocytes, respectively. However, there were no significant difference in OXPHOS Cx (Cx III–V) protein expression between control and H₂O₂-treated ONH astrocytes. We also found that pretreatment of CoQ₁₀ significantly decreased OXPHOS Cx (Cx I, II and V) protein expression by 0.33 ± 0.06 - ($P<0.001$), 1.36 ± 0.16 - ($P<0.01$), and 0.62 ± 0.07 -fold ($P<0.05$), respectively, compared with ONH astrocytes exposed to H₂O₂. However, there was no significant difference in OXPHOS Cx (Cx III and IV) protein

expression between H₂O₂- and CoQ₁₀/H₂O₂-treated ONH astrocytes, indicating that CoQ₁₀ may preserve OXPHOS Cx protein expression in the ONH astrocytes against oxidative stress.

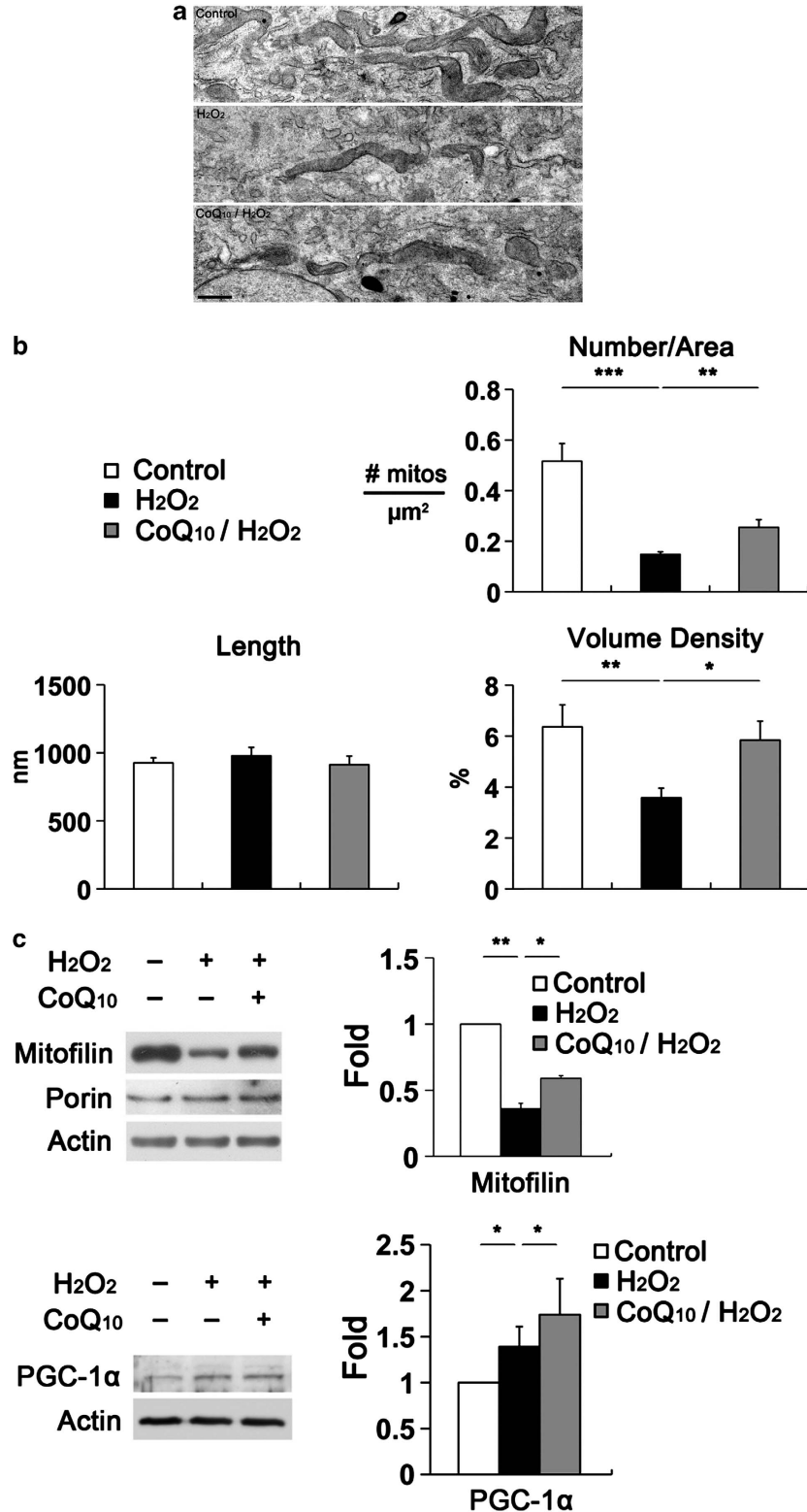
CoQ₁₀ prevents alteration of mitochondrial bioenergetics due to oxidative stress. To determine whether H₂O₂-induced oxidative stress alters mitochondrial bioenergetics in ONH astrocytes and whether CoQ₁₀ treatment inhibits the alteration of mitochondrial bioenergetics, we measured cell viability, ROS generation and cellular ATP level. As shown in Figure 7, our findings show that H₂O₂-induced oxidative stress significantly decreased cell viability to $80.8 \pm 5.4\%$ of the control value in the ONH astrocytes ($P<0.05$). However, pretreatment of CoQ₁₀ significantly boosted cell viability to $92.6 \pm 4.6\%$ in the ONH astrocytes exposed to H₂O₂ ($P=0.001$). In comparison with control ONH astrocytes, H₂O₂-induced oxidative stress significantly increased ROS generation by 7.82 ± 0.81 -fold over the control in the ONH astrocytes ($P=0.01$). In contrast, pretreatment of CoQ₁₀ significantly decreased ROS generation to 4.67 ± 0.83 -fold of the control in the ONH astrocytes exposed to H₂O₂ ($P<0.05$). In addition, we found that H₂O₂-induced oxidative stress significantly decreased the cellular ATP level to $83.8 \pm 3.7\%$ of the control value in the ONH astrocytes ($P<0.01$). However, pretreatment of CoQ₁₀ nearly completely restored the cellular ATP level ($96.9 \pm 4.3\%$ of the control) in the ONH astrocytes exposed to H₂O₂ ($P<0.05$), suggesting that CoQ₁₀ restores bioenergetic function in the ONH astrocytes to counter oxidative stress.

Discussion

We addressed the question of whether oxidative stress triggers mitochondria-mediated dysfunction in the ONH

astrocytes because oxidative stress has been implicated as an important pathophysiological mechanisms in the pathogenesis of glaucoma.^{4,9,31,32} It has been proposed that

reduction of oxidative stress could be protective in glaucomatous ONH treatment^{24,33-35} and that mitochondrial dysfunction may have a critical role in oxidative stress-mediated glaucomatous



neurodegeneration.^{2,4,5,36,37} Interestingly, oxidative stress leads to antioxidant or immune responses in human ONH astrocytes.^{24,32,38} Support for our investigations came from a

recent study demonstrating oxidative stress, mitochondrial dysfunction and Ca²⁺ overload in GFAP-negative human lamina cribrosa cells in the ONH from glaucoma donor eyes.³

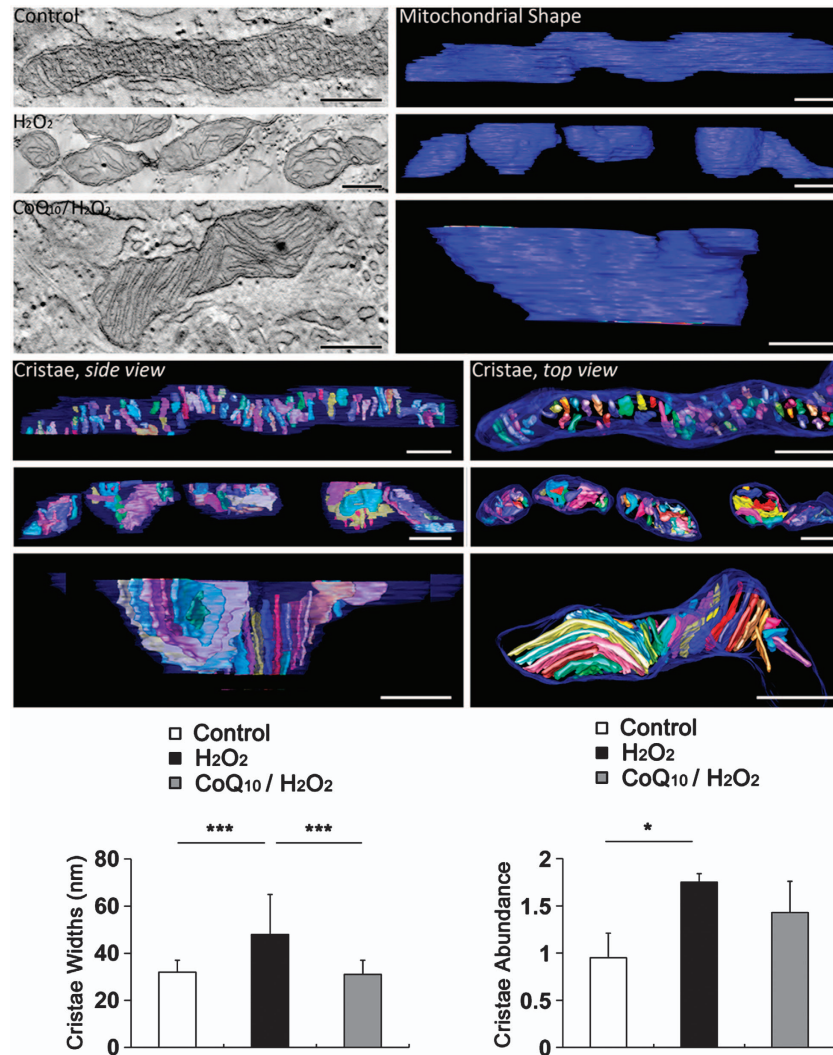


Figure 4 CoQ₁₀ triggers mitochondrial biogenesis in ONH astrocytes that counters oxidative stress. (a) The representative 2D images from TEM analysis showed that control ONH astrocytes exposed to vehicle contained classic elongated tubular mitochondria. However, ONH astrocytes exposed to H₂O₂ contained fewer mitochondria in the ONH astrocytes. Interestingly, ONH astrocytes pretreated with CoQ₁₀ showed a greater number compared with the ONH astrocytes exposed to H₂O₂. (b) Quantitative analysis showed that mitochondrial number per area and volume density were significantly decreased in the ONH astrocytes exposed to H₂O₂. However, ONH astrocytes pretreated with CoQ₁₀ had a significant increase in mitochondrial number and volume density compared with the ONH astrocytes exposed to H₂O₂. There was no difference in mitochondrial length among control, H₂O₂ and CoQ₁₀/H₂O₂-treated ONH astrocytes. Values are mean ± S.E.M. * $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$ compared with vehicle-treated control ONH astrocytes or H₂O₂-treated ONH astrocytes. Scale bar, 500 nm. (c) Mitofilin protein expression was significantly increased in the ONH astrocytes exposed to H₂O₂ compared with vehicle-treated control ONH astrocytes. In contrast, CoQ₁₀ significantly increased mitofilin protein expression compared with ONH astrocytes exposed to H₂O₂. PGC-1 α protein expression was significantly increased in the ONH astrocytes exposed to H₂O₂ compared with vehicle-treated control ONH astrocytes. Of interest, pretreatment of CoQ₁₀ showed greater increase of PGC-1 α protein expression in the ONH astrocytes exposed to H₂O₂. Relative intensity of chemiluminescence for each protein band was normalized using actin. Values are mean ± S.D. ($n = 3$). CoQ₁₀, coenzyme Q10; H₂O₂, hydrogen peroxide

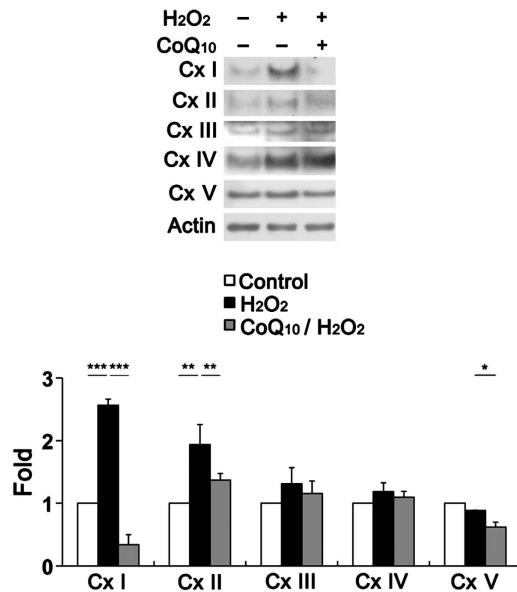


Figure 6 CoQ₁₀ preserves OXPHOS Cx protein expression against oxidative stress. In comparison with control ONH astrocytes, H₂O₂-induced oxidative stress significantly increased OXPHOS Cx (Cx I and II) protein expression in the ONH astrocytes. However, there was no significant difference in OXPHOS Cx (Cx III–V) protein expression. Pretreatment of CoQ₁₀ significantly decreased OXPHOS Cx (Cx I, II and V) protein expression compared with ONH astrocytes exposed to H₂O₂. However, there was no significant difference in OXPHOS Cx (Cx III and IV) protein expression between H₂O₂- and CoQ₁₀/H₂O₂-treated ONH astrocytes. Values are mean ± S.D. **P* < 0.05, ***P* < 0.01 and ****P* < 0.001 compared with vehicle-treated control ONH astrocytes or H₂O₂-treated ONH astrocytes. CoQ₁₀, coenzyme Q10; H₂O₂, hydrogen peroxide; OXPHOS, oxidative phosphorylation; Cx, complex

CoQ₁₀ is an attractive antioxidant and neurotherapeutic agent for us to test efficacy in glaucoma because published evidence supports its effectiveness against oxidative stress in many neurodegenerative diseases including Parkinson' and Huntington' diseases.^{15,39,40} Recent studies increasingly demonstrated that CoQ₁₀ is neuroprotective in retinal cells *in vivo* and *in vitro* against pressure, oxidative stress, excitotoxicity, or apoptotic radiation.^{19,21,22,41,42} In the current study, we found that oxidative stress triggers the activation of ONH astrocytes as well as the upregulation of SOD2 and HO-1 protein expression in the ONH astrocytes. In contrast, CoQ₁₀ not only prevents activation of ONH astrocytes but also significantly decreases SOD2 and HO-1 protein expression in the ONH astrocytes against oxidative stress. The upregulation of antioxidant enzymes such as SOD2 in astrocytes is accompanied by a higher resistance to oxidative stress induced by H₂O₂.⁴³ In addition, SOD2 activity directly stabilizes mitochondrial transmembrane potential and calcium-buffering ability.⁴⁴ Together with these findings, our results, therefore, raise the possibility that increasing SOD2 or HO-1 expression in the ONH astrocytes may contribute to compensatory endogenous antioxidant mechanisms that increase resistance or stabilization of mitochondria against oxidative stress. In addition, these results reflect that CoQ₁₀ could be an important antioxidant for ameliorating oxidative stress-mediated dysfunction in the ONH astrocyte. We believe that studying the benefits of CoQ₁₀-mediated blockade of oxidative stress or enhancement of antioxidant enzymes

in the ONH astrocytes may be rewarding in many optic neuropathy including glaucoma.

We further addressed the relationship between oxidative stress and the mitochondrial network in the ONH astrocytes. We demonstrated for the first time that oxidative stress induced a significant loss of mitochondrial mass by decreasing mitochondrial number and volume density in the ONH astrocytes. However, CoQ₁₀ treatment showed a partial inhibition of mitochondrial loss by increasing mitochondrial number and volume density in the ONH astrocytes, suggesting that CoQ₁₀ could protect ONH astrocytes by triggering mitochondrial biogenesis. In agreement with these findings, we also observed that oxidative stress significantly reduced the expression level of mitofilin protein in the ONH astrocytes. However, there was no significant difference in porin expression among groups, suggesting that the observed increase in number of mitochondria did not produce significantly more outer membrane where porin resides or alternatively that porin was diluted upon mitochondrial biogenesis. Intriguingly, CoQ₁₀ treatment partially increased mitofilin protein expression in the ONH astrocytes against oxidative stress. More importantly, we also found that CoQ₁₀ treatment showed greater increase of PGC-1 α protein expression in the ONH astrocytes to protect against oxidative stress.

Mitofilin is anchored to the mitochondrial inner membrane and controls mitochondrial cristae morphology.²⁶ As a previous study suggests that mitofilin depletion decreases cellular proliferation and increases apoptosis, as well as triggers mitochondrial structural and functional abnormalities,²⁶ it is possible that a significant loss of mitofilin protein expression by oxidative stress may result in structural and functional dysfunction of mitochondria in the ONH astrocytes. PGC-1 α activates mitochondrial biogenesis and oxidative metabolism^{45,46} as well as regulates the transcription target proteins such as nuclear-encoded respiratory Cx proteins and mitochondrial transcription factor A that has an important role in mitochondrial gene expression and mitochondrial DNA maintenance, and therefore is essential for OXPHOS-mediated ATP synthesis.^{45,47,48} Collectively, therefore, increasing mitofilin or PGC-1 α protein expression by CoQ₁₀ treatment also raises the intriguing possibility that mitofilin or PGC-1 α can be a therapeutic target for protecting mitochondria or promoting mitochondrial biogenesis, especially cristae biogenesis or stabilization of the ONH astrocytes to counter oxidative stress-mediated mitochondrial dysfunction. In addition, we found that oxidative stress significantly increased cristae widths and abundance in the mitochondria of the ONH astrocytes. However, CoQ₁₀ treatment significantly preserved cristae widths, but partially preserved cristae abundance in the mitochondria of the ONH astrocytes against oxidative stress, suggesting that CoQ₁₀ can modulate mitochondrial cristae structure in the ONH astrocytes to protect against oxidative damage. Altogether, our findings suggest that CoQ₁₀ may have a therapeutic potential for ameliorating oxidative stress-induced alteration of the mitochondrial network in the ONH astrocytes. Future studies are needed to address how CoQ₁₀ directly promotes mitochondrial biogenesis and structural preservation in the ONH astrocytes against oxidative stress and whether oxidative stress-mediated mitofilin loss directly alters mitochondrial cristae morphology.

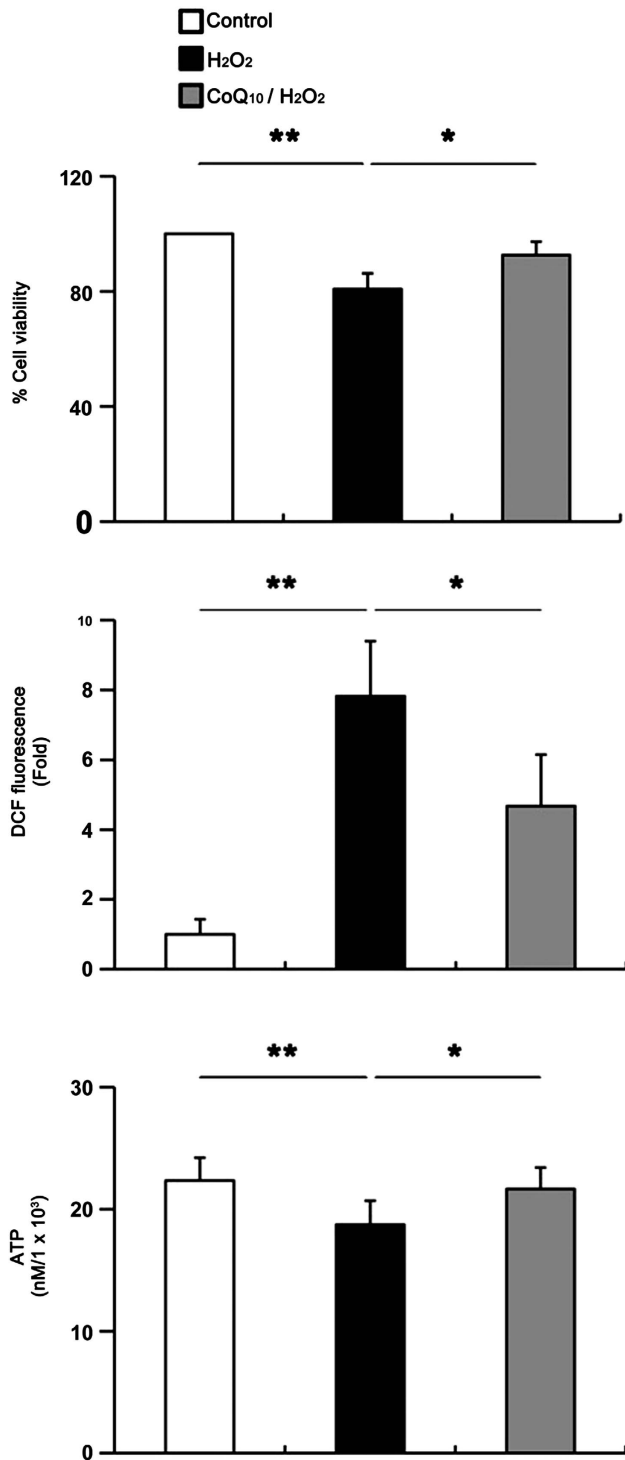


Figure 7 CoQ₁₀ prevents the alteration of mitochondrial bioenergetics caused by oxidative stress. Pretreatment of CoQ₁₀ significantly restored cell viability to $92.6 \pm 4.6\%$ of the control level in the ONH astrocytes exposed to H₂O₂. In comparison with control ONH astrocytes, H₂O₂-induced oxidative stress significantly increased ROS generation in the ONH astrocytes. In contrast, pretreatment of CoQ₁₀ significantly decreased ROS generation in the ONH astrocytes exposed to H₂O₂. In addition, H₂O₂-induced oxidative stress significantly decreased the cellular ATP level in the ONH astrocytes. However, pretreatment of CoQ₁₀ significantly restored the cellular ATP level in the ONH astrocytes exposed to H₂O₂. Values are mean \pm S.D. * $P < 0.05$ and ** $P < 0.01$ compared with vehicle-treated control ONH astrocytes or H₂O₂-treated ONH astrocytes. CoQ₁₀, coenzyme Q10; H₂O₂, hydrogen peroxide

In the current study, we found that oxidative stress triggered the upregulation of OXPHOS Cxs (Cx I–IV) protein expression in the ONH astrocytes. However, CoQ₁₀ treatment preserved OXPHOS Cx protein expression including the ATP synthase against oxidative stress. CoQ₁₀ regulates the mitochondrial OXPHOS system and prevents lipid peroxidation.^{49,50} It has been demonstrated that a defective OXPHOS system may be induced by an insufficient fuel supply, defective electron transport chain enzymes (Cx I–IV) or lack of the electron carrier CoQ₁₀.⁴⁹ In addition, CoQ₁₀ treatment significantly increases ATP synthetic capacity in lymphocytes from patients as well as in cultured control lymphocytes *in vitro*,²⁸ suggesting that CoQ₁₀ may have a beneficial effect in the treatment of OXPHOS disorders.^{28,29} Although further investigations are needed, it is possible that oxidative stress may induce CoQ₁₀ deficiency in ONH astrocytes, triggering alteration of the OXPHOS system. Further, our findings showed that CoQ₁₀-mediated partial preservation of mitochondrial cristae abundance supports CoQ₁₀-mediated increase of certain OXPHOS Cxs against oxidative stress. Thus, our results reflect that the upregulation of OXPHOS Cx protein expression may contribute to a critical endogenous defense mechanism for protecting mitochondria of the ONH astrocytes against oxidative stress.

Oxidative stress-mediated ROS alters OXPHOS function.^{51,52} This alteration of mitochondrial OXPHOS Cxs by oxidative stress in turn leads to reduction of ATP production and increase of ROS generation, consistent with our results.² Further, increased ROS generation results in mitochondrial bioenergetic dysfunction in many neurodegenerative diseases,^{53,54} suggesting an oxidative stress-mediated mitochondrial vicious cycle involved in neurodegeneration that includes oxidative stress, ROS production, OXPHOS alteration and mitochondrial bioenergetic dysfunction. In the current study, we found that oxidative stress triggers an excessive increase of ROS generation, reduction of cellular ATP level and subsequent decrease of cell viability in the ONH astrocytes. Of note, we found that CoQ₁₀ treatment decreases ROS generation, increases cellular ATP production, and promotes cell viability in ONH astrocytes. It was shown that CoQ₁₀ improves mitochondrial bioenergetic parameters such as oxygen consumption rate, mitochondrial transmembrane potential and ATP synthesis in cultured T62 and H9c2 cell lines consistent with its role in the mitochondrial respiratory chain.⁵⁵ Moreover, a recent study demonstrated that CoQ₁₀ deficiency is associated with oxidative stress, increased ROS production, defective ATP synthesis and cell death.⁵⁶ Our findings also showed that oxidative stress triggered abnormal cristae morphology such as cristae dilation in the mitochondria of the ONH astrocytes. Moreover, because activation of PGC-1 α correlates with increased cellular energy demand,⁵⁷ a significant increase of PGC-1 α may reflect an increased energy demand from the mitochondria of ONH astrocytes against oxidative stress. This correlates with our findings of reduced ATP production. Altogether, these findings strongly suggest that CoQ₁₀ supplementation may have therapeutic potential for ameliorating a mitochondrial vicious cycle involved in ONH degeneration that includes oxidative stress, OXPHOS dysfunction, ROS generation and bioenergetics impairment in the ONH

astrocytes during glaucomatous neurodegeneration. Finally, we believe that it would be useful to measure the origin of the energy defect by pharmacologically inhibiting glycolytic and mitochondrial pathways in the future studies.

On the basis of these observations, we suggest that oxidative stress-mediated mitochondrial dysfunction or alteration may be important pathophysiological mechanisms in the dysfunction of ONH astrocytes. Therefore, treatment with CoQ₁₀ may be neuroprotective and protect ONH astrocytes against oxidative stress-mediated mitochondrial dysfunction or alteration in glaucoma and other optic neuropathies.

Materials and Methods

Animals. Pregnant Sprague–Dawley rats (250–300 g in weight; Harlan Laboratories, Indianapolis, IN, USA) were housed in covered cages, fed with a standard rodent diet *ad libitum*, and kept on a 12-h light/12-h dark cycle. All procedures concerning animals were in accordance with the ARVO Statement for the Use of Animals in Ophthalmic Vision Research and under protocols approved by institutional IACUC committees at the University of California, San Diego.

Isolation and culture of rat ONH astrocytes. Primary rat ONH astrocyte cultures were modified and derived as previously described.²³ After euthanizing with CO₂ gas, 10–20 pieces of ONH tissue were dissected from postnatal day 5 Sprague–Dawley rats and transferred to a 35-mm petri dish with 2 ml 0.2% bovine serum albumin (BSA)/Dulbecco's phosphate-buffered saline (DPBS). Under a dissecting microscope, pigmented and remnant non-neuronal tissues such as sclera and other neighboring tissues were removed, and the ONH tissue was identified and dissected using a microscissor and sharp blade. The ONH tissue was minced and transferred to a 60-mm petri dish and conditioned with growth medium: GlutaMAX/Dulbecco's modified Eagle's medium (DMEM) supplemented with 10% fetal bovine serum (FBS), 100 U/ml penicillin and 100 µg/ml streptomycin (Invitrogen, La Jolla, CA, USA), and prewarmed in a humidified atmosphere 5% CO₂ incubator at 37 °C. After incubation for 10 days, the ONH explants were removed by 70-µm cell strainers (BD, Sparks, MD, USA). The cells that were grown from the ONH explants were plated in a 100-mm petri dish and incubated for 3 days at 37 °C. For further purification of the ONH astrocytes, the growth medium was changed to serum-deprived medium and the culture dish was shaken for 24 h at room temperature. After removing nonadherent cells, the adherent ONH astrocytes were collected, centrifuged and replated on poly-L-lysine-coated culture dishes. The homogeneity of ONH astrocyte cultures was evaluated by western blot analysis or immunohistochemistry as below.

Pharmacological treatment. Three groups of rat ONH astrocytes were studied following treatment of H₂O₂ or CoQ₁₀: a group treated with vehicle (chloroform; Sigma, St. Louis, MO, USA), a group treated with 100 µM H₂O₂ (Sigma), and a group treated with CoQ₁₀ (50 µg/ml in chloroform, Sigma) and 100 µM H₂O₂ (Sigma). H₂O₂ was treated in 1% FBS/DMEM/Ham's F12 50/50 (DMEM/F12) for 1 h in a 5% CO₂ incubator at 37 °C. CoQ₁₀ was pre-incubated with 1% FBS/DMEM/F12 for 24 h and treated with H₂O₂ with DMEM/F12 for 1 h in a 5% CO₂ incubator at 37 °C.

Western blot analysis. Rat ONH astrocytes were lysed with lysis buffer (20 mM HEPES pH 7.0, 1% TritonX-100, 10% glycerol, 2 mM EGTA, 1 mM EDTA pH 8.0 (w/NaOH), 20 mM β-glycerolphosphate, complete protease inhibitors (Roche Biochemicals, Indianapolis, IN, USA) and phosphatase inhibitors (1 µg/ml Aprotinin, 1 µg/ml Leupeptin, 1 mM AEBFS, 1 mM Na₃VO₄, 5 mM NaF and 2.5 mM Microcystin-LR)). Each sample (10 mg proteins per well) was loaded and separated based on the molecular weights by SDS-PAGE and electrotransferred to polyvinylidene difluoride membranes. The membranes were blocked with 5% nonfat dry milk with 0.1% Tween-20 in PBS (PBST) for 1 h at room temperature and incubated with primary antibodies at 4 °C for overnight. The primary antibodies used were mouse monoclonal anti-GFAP antibody (1 : 3000; Sigma), rabbit polyclonal anti-Iba1 antibody (1 : 500; Wako Chemicals, Richmond, VA, USA), rabbit polyclonal anti-MBP antibody (1 : 1000; Abcam, Cambridge, MA, USA), rabbit polyclonal anti-SOD2 antibody (1 : 2000; Santa Cruz Biotechnology, Santa Cruz, CA, USA), rabbit polyclonal anti-HO-1 antibody (1 : 5000; Stressgen

Bioreagents, San Diego, CA, USA), mouse monoclonal anti-mitofilin antibody (1 : 500; Mitosciences, Eugene, OR, USA), rabbit polyclonal anti-PGC-1α (1 : 1000; Santa Cruz Biotechnology), mouse monoclonal anti-total OXPHOS Cx antibody (containing a mixture of antibodies to CxI-IV and ATP synthase, 1 : 3000; Invitrogen), rabbit polyclonal anti-porin antibody (1 : 2000; Calbiochem, Rockland, MA, USA) and mouse monoclonal anti-actin antibody (1 : 5000; Millipore, Billerica, MA, USA). After several washes with PBST, the membranes were incubated for 1 h at room temperature with horseradish peroxidase-conjugated goat anti-mouse IgG (1 : 5000; Bio-Rad, Hercules, CA, USA) or goat anti-rabbit IgG (1 : 5000; Bio-Rad) and developed by chemiluminescence detection. The density of protein bands from the scanned images was analyzed using ImageJ (<http://www.rsbl.info.nih.gov/ij/>).

Immunocytochemical analysis. Immunofluorescent staining of cultured ONH astrocytes was performed as previously described.¹¹ Briefly, the cells were fixed with 4% paraformaldehyde (Sigma)/PBS for 1 h at room temperature. To prevent nonspecific background, the cells were incubated in 1% BSA/PBS for 1 h at room temperature before incubation with mouse monoclonal anti-GFAP antibody (1 : 300; Sigma) and rabbit polyclonal anti-SOD2 antibody (1 : 2000; Santa Cruz Biotechnology) for 16 h at 4 °C. After several wash steps, the cells were incubated with the secondary antibody, Alexa Fluor 488 dye-conjugated goat anti-mouse IgG antibody (1 : 100; Invitrogen) or Alexa Fluor 488 dye-conjugated goat anti-rabbit IgG antibody (1 : 100; Invitrogen) for 4 h at 4 °C and subsequently washed with PBS. The cells were counterstained with the nucleic acid stain Hoechst 33342 (1 µg/ml, Life Technologies, Grand Island, NY, USA) in PBS. Images were acquired with confocal microscopy (Olympus FluoView1000; Olympus, Tokyo, Japan).

Morphology analysis for mitochondria. Mitochondria in the ONH astrocytes were labeled by the addition of a red fluorescent mitochondrial dye to the cultures (100 nM final concentration; MitoTracker Red CMXRos; Invitrogen-Molecular Probes) and maintaining it for 20 min in a CO₂ incubator. This dye is concentrated in active mitochondria by a process that is dependent on mitochondrial membrane potential (i.e., accumulation is inhibited by actinomycin A but not by rotenone). The cultures were subsequently fixed with 4% paraformaldehyde (Sigma) in DPBS for 30 min at 4 °C and counterstained with Hoechst 33342 (1 µg/ml; Invitrogen-Molecular Probes) in DPBS. For a 3D reconstruction, images were obtained with optical section separation (z-interval) of 0.25 µm by Olympus FluoView1000. Isosurface rendition was obtained from the stack using Imaris 6.4.2 (Bitplane AG, Zurich, Switzerland).

Electron microscopy. For conventional electron microscopy, cultured ONH astrocytes after treatment were fixed with 2% paraformaldehyde, 2.5% glutaraldehyde (Ted Pella, Redding, CA, USA) in 0.15 M sodium cacodylate (pH 7.4) at 37 °C and placed in pre-cooled fixative on ice for 1 h. The following procedure was used to optimize mitochondrial structural preservation and membrane contrast. The cells were post-fixed with 1% osmium tetroxide, 0.8% potassium ferrocyanide, 3 mM calcium chloride in 0.1 M sodium cacodylate (pH 7.4) for 1 h, washed with ice-cold distilled water, post-stained with 2% uranyl acetate at 4 °C, dehydrated using graded ethanols, and embedded in Durcupan resin (Fluka, St. Louis, MO, USA). Ultrathin (70 nm) sections were post-stained with uranyl acetate and lead salts and evaluated by a JEOL 1200FX (JEOL, Tokyo, Japan) TEM operated at 80 kV. Images were recorded on film at × 8000 magnification. The negatives were digitized at 1800 dpi using a Nikon Cool scan system (Nikon Instruments Inc., Melville, NY, USA), giving an image size of 4033 × 6010 pixel array and a pixel resolution of 1.77 nm. Mitochondrial lengths were measured with ImageJ. The mitochondrial volume density, defined as the volume occupied by mitochondria divided by the volume occupied by the cytoplasm, was estimated using stereology as follows. A 112 × 112 square grid (112 × 112 chosen for ease of use with Photoshop) was overlaid on each image loaded in Photoshop (Adobe Systems Inc., San Jose, CA, USA), and the mitochondria and cytoplasm lying under intercepts were counted. The relative volume of the mitochondria was expressed as the ratio of intercepts coinciding with this organelle relative to the intercepts coinciding with the cytoplasm.

Electron microscope tomography. Sections of cells from each group were cut at thicknesses of 400–500 nm. Sections were then stained 30 min in 2% aqueous uranyl acetate, followed by 15 min in lead salts. Fiducial cues consisting of 20 nm and colloidal gold particles were deposited on opposite sides of the section.

For each reconstruction, a series of images at regular tilt increments was collected with a JEOL 4000EX intermediate-voltage electron microscope operated at 400 kV. The specimens were irradiated before initiating a tilt series in order to limit anisotropic specimen thinning during image collection. Tilt series were recorded using a $4 \times 4 \text{ k}^2$ CCD camera with an angular increment of 2° from -60° to $+60^\circ$ about an axis perpendicular to the optical axis of the microscope using a computer-controlled goniometer to increment accurately the angular steps. The illumination was held to near parallel beam conditions and optical density was maintained constant by varying the exposure time. The magnification was 12 000 and the pixel resolution was 1.2 nm. The IMOD package (<http://bio3d.colorado.edu/imod/>) was used for rough alignment with the fine alignment and reconstruction was performed using the TxBR package (National Center for Microscopy and Imaging Research, San Diego, CA, USA). Volume segmentation was performed by manual tracing in the planes of highest resolution with the program Xvotrace.⁵⁸ The mitochondrial reconstructions were visualized using Analyze (Mayo Foundation, Rochester, MN, USA) or the surface-rendering graphics of Synu (National Center for Microscopy and Imaging Research, San Diego, CA, USA) as described.⁵⁸ These programs allow one to step through slices of the reconstruction in any orientation and to track or model features of interest in three dimensions.

Cell viability measurement. Cell viability was measured using 3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyl tetrazolium bromide (MTT) according to the manufacturer's recommendations (Cell Proliferation Kit 1; Roche Diagnostics, Indianapolis, IN, USA). Briefly, ONH astrocytes were plated on a 96-well plate (1×10^3 per well) and after 24 h, the cells were pre-incubated with $50 \mu\text{g/ml}$ CoQ₁₀ for 24 h, and then exposed to H₂O₂. At various times, a mixture of 100-ml fresh medium and $10\text{-}\mu\text{l}$ MTT stock solution was added to each well including the negative control. The cells were incubated for 4 h in a humidified atmosphere of a 5% CO₂ incubator at 37 °C, $100 \mu\text{l}$ of solubilization solution was added per well to resolve the crystallized formazan. After incubation for 16–18 h in a humidified atmosphere of a 5% CO₂ incubator at 37 °C, the absorbance at 560 nm was measured with a microplate reader (Spectra MAX; Molecular Devices Corp., Sunnyvale, CA, USA). Each set of data was collected from multiple replicate wells of each experimental group ($n=3$).

ROS measurement. The intracellular ROS was measured by 5-(and-6)-chloromethyl-2',7'-dichlorodihydrofluorescein diacetate, acetyl ester (CM-H₂DCFDA, Life Technologies), a chloromethyl derivative of H₂DCFDA, useful as an indicator for ROS in cells. Briefly, ONH astrocytes were plated on a six-well plate (1.7×10^4 per well) and after 24 h, cells were pre-incubated with $50 \mu\text{g/ml}$ CoQ₁₀ for 24 h, and then exposed to H₂O₂. The cells were detached with trypsin/EDTA and loaded with $20 \mu\text{M}$ CM-H₂DCFDA at 37 °C for 20 min, and then fluorescence of the sample was measured immediately using flow cytometry (BD FACSCanto II, BD Bioscience, San Diego, CA, USA). Each set of data was collected from multiple replicate dishes of each experimental group ($n=3$).

Cellular ATP measurement. ATP levels were measured using a luciferase-based assay kit (CellTiter-Glo, Promega Corp., Madison, WI, USA). Briefly, ONH astrocytes were plated on a 96-well plate (1×10^3 per well) and after 24 h, the cells were pre-incubated with $50 \mu\text{g/ml}$ CoQ₁₀ for 24 h, and then exposed to H₂O₂. ATP standard curves from 0 to 1000 nM of ATP in growth media were prepared. After H₂O₂ treatment, $100 \mu\text{l}$ growth media was added, followed by $100 \mu\text{l}$ of the CellTiter-Glo reagent per well to lyse cells using vigorous shaking for 2 min at room temperature. At this point, the prepared ATP standard solution was added. To stabilize the luminescence signal, cells at room temperature were incubated for 10 min. The luminescence was measured using a microplate luminometer (Labsystems Luminoskan, GMI Inc., Minneapolis, MN, USA). Each set of data was collected from multiple replicate wells of each experimental group ($n=3$).

Statistical analysis. Data were presented as the mean \pm S.D. or S.E.M. Comparison of two or three experimental conditions was evaluated using the unpaired, two-tailed Student's *t*-test or one-way analysis of variance and the Bonferroni *t*-test. $P < 0.05$ was considered statistically significant.

Conflict of Interest

The authors declare no conflict of interest.

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