

Article

A Dietary Combination of Forskolin with Homotaurine, Spearmint and B Vitamins Protects Injured Retinal Ganglion Cells in a Rodent Model of Hypertensive Glaucoma

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Abstract: There is indication that nutritional supplements protect retinal cells from degeneration. In a previous study, we demonstrated that dietary supplementation with an association of forskolin, homotaurine, spearmint extract and B vitamins efficiently counteracts retinal dysfunction associated with retinal ganglion cell (RGC) death caused by optic nerve crush. We extended our investigation on the efficacy of dietary supplementation with the use of a mouse model in which RGC degeneration depends as closely as possible on intraocular pressure (IOP) elevation. In this model, injecting the anterior chamber of the eye with methylcellulose (MCE) causes IOP elevation leading to RGC dysfunction. The MCE model was characterized in terms of IOP elevation, retinal dysfunction as determined by electrophysiological recordings, RGC loss as determined by brain-specific homeobox/POU domain protein 3A immunoreactivity and dysregulated levels of inflammatory and apoptotic markers. Except for IOP elevation, dysfunctional retinal parameters were all recovered by dietary supplementation indicating the involvement of non-IOP-related neuroprotective mechanisms of action. Our hypothesis is that the diet supplement may be used to counteract the inflammatory processes triggered by glial cell activation, thus leading to spared RGC loss and the preservation of visual dysfunction. In this respect, the present compound may be viewed as a potential remedy to be added to the currently approved drug therapies for improving RGC protection.

Keywords: intraocular pressure elevation; retinal function; full-field electroretinogram; pattern electroretinogram; gliosis; inflammation; apoptosis; bioactive compounds; neuroprotection

1. Introduction

Glaucoma is a neurodegenerative disorder characterized by the degeneration of retinal ganglion cells (RGCs) and their axons and is the leading cause of irreversible blindness and visual impairment in developed countries, expected to affect more than 110 million people by 2040 [1]. Glaucoma is presently considered an age-dependent disease with pathogenetic mechanisms common to those of additional neurodegenerative pathologies of the elderly, including Alzheimer’s disease [2], with a growing incidence linked to the increasing number of people of advanced age. In addition, the growing global problem of myopia, with its drastic rise in Asian countries, is likely to

increase the incidence of glaucoma because the laser-assisted corneal refractive surgery is an important risk factor for intraocular pressure (IOP) elevation [3].

In hypertensive glaucoma, visual loss is believed to be caused by RGC dysfunction associated with IOP elevation, although the exact cause of RGC degeneration is still debated. In addition, there is still some debate about a causal relationship between RGC dysfunction and visual loss since RGC axon degeneration preceding neuronal loss may crucially determine the visual field impairment that characterizes glaucoma [4]. While significant RGC apoptosis has been observed in glaucoma models [5] evidence of apoptotic RGC death in human glaucoma is scarce, although new imaging techniques may allow the detection of apoptotic retinal cells in glaucoma patients [6]. In addition, a good agreement between the loss in retinal sensitivity and the thickness of the RGC layer has been recently reported in glaucoma patients [7]. Moreover, in glaucoma models, ocular hypertension has been shown to lead to a progressive apoptosis of retinal neurons starting in the ganglion cell layer and spreading to the inner nuclear layer and then the outer nuclear layer, thus making it difficult to explain the structure–function relationship in response to IOP elevation [8,9].

Although approved treatments for hypertensive glaucoma rely on the use of drugs able to reduce IOP, the causal relationship between IOP elevation, RGC degeneration and visual loss is not that easy. Indeed, glaucoma patients may continue to experience disease progression despite IOP reduction, indicating that decreasing IOP is not always the solution to prevent the disease [10]. In animal models, RGC death may also occur despite normal IOP and reduced IOP does not necessarily couple to RGC rescue, thus suggesting the involvement of additional risk factors [11].

The use of neuroprotective treatments in combination with IOP-lowering drugs deserves further attention at the preclinical level and a lot of effort is being made to develop novel neuroprotective molecules that might prevent RGC loss, although their transformation to clinic has not been fruitful (see for ref. [12]). In particular, results from clinical trials are less promising depending on the tolerability of putative neuroprotective compounds that may limit their use [13]. In a successful case history as in low-pressure glaucoma patients, treatment with the alpha-adrenergic agonist brimonidine (endowed with both hypotensive and neuroprotective effects) is more likely to prevent from visual field progression than the beta blocker timolol [14].

In the search for neuroprotectant compounds, much attention has been recently paid to the use of nutritional supplements to counteract ocular pathologies. In both glaucoma models and glaucomatous patients, there are several indications for the efficacy of nutritional supplements in protecting retinal cells from degeneration [15,16]. For instance, dietary resveratrol or α lipoic acid are protective against RGC death in glaucoma models [17,18]. In addition, dietary supplementation with antioxidants has been shown to efficiently counteract human glaucomatous-related pathologies by increasing blood circulation to the optic nerve and promoting RGC survival [19]. Recently, dietary supplementation with an association of forskolin, homotaurine, spearmint extract and B vitamins has been demonstrated to efficiently counteract retinal dysfunction associated with RGC death caused by optic nerve crush (ONC) [20]. These findings have laid the foundation for future work in models in which RGC degeneration may depend as closely as possible on IOP elevation.

In humans, IOP depends on the rate of aqueous humor production and the rate of its main drainage through the trabecular meshwork and the canal of Schlemm; IOP greater than 21 mm Hg is referred to as ocular hypertension [21]. In rodent models, IOP elevation can be obtained with different strategies more or less mimicking what happens in the human pathology. Although the eye anatomy in rodents differs from that in humans, the similarity in the conventional outflow pathway renders the rodent eye a suitable model to mimic the changes observed in human glaucomatous eyes. In rodent models, IOP elevation can be obtained by increasing aqueous humor outflow resistance as for instance through the blockade of the trabecular meshwork or through the closure of episcleral veins [22].

In the present study, we extended our previous investigation on the efficacy of a diet supplementation with an association of forskolin, homotaurine—a taurine analog that mimics GABA, spearmint extract with antioxidant activity and B vitamins with major efficacy against ocular diseases in a model of RGC degeneration induced by ONC [20] to an animal model in which injecting the anterior chamber of the eye with methylcellulose (MCE) causes IOP elevation,

eventually leading to RGC dysfunction. This model was developed in rabbits [23] and successfully applied in the rats [24]. In the present study, the MCE model was established in mice taking into consideration that the anatomy and the physiology of the aqueous humor outflow does not differ between rats and mice [22]. In addition, in mice, hydroxypropyl MCE is able to increase the microbeads-induced IOP elevation due to the high viscosity of MCE and its derivatives [25]. After having characterized the MCE model in the mouse, we determined whether diet supplementation with the above associated compounds can efficiently counteract MCE-induced IOP elevation and its detrimental effects on RGCs structure and function. IOP was monitored for two weeks before and two weeks after MCE injection. Full-field electroretinograms (ERG) and pattern ERGs (PERG) were recorded, and whether they were influenced by dietary supplementation, retinas were assessed *ex vivo* as whole mounts for RGC detection and quantitation by immunohistochemistry for brain-specific homeobox/POU domain protein 3A (Brn3a), a transcription factor that is considered a specific and reliable marker of RGCs giving indirect indications of the functional state of these cells [26]. Mechanisms underlying neuroprotective effects of the diet supplementation were investigated by evaluating whether the diet affects MCE-associated inflammatory processes and apoptotic cascade.

2. Materials and Methods

2.1. Animals

This study was executed in agreement with the Association for Research in Vision and Ophthalmology (ARVO) Statement for the Use of Animals in Ophthalmic and Vision Research and the Guide for the Care and Use of Laboratory Animals of the National Institutes of Health. The present study also adheres to the European Communities Council Directive (2010/63/UE) and the Italian guidelines for animal care (DL 26/14). The experimental protocol was approved by the Commission for Animal Wellbeing of the University of Pisa (permit number: 0009069/2014). The number of mice used in the present study, as well as their suffering, was limited according to the 3Rs principles for ethical use of animals in scientific research. C57BL/6 mice were from Charles River Laboratories Italy (Calco, Italy). They were mated in the animal facility of the Department of Biology in order to establish a breeding colony. Sixty-six mice either male or female (8 weeks old) were used. Of them, 33 mice were used as controls (11 left untreated, 11 fed with vehicle, 11 fed with the diet supplement), while 33 mice were used as a model of intraocular hypertension (11 left untreated, 11 fed with vehicle, 11 fed with the diet supplement).

2.2. Experimental Model of Intraocular Hypertension

The model is based on the injection of MCE (2% in sterile water) in the anterior chamber of the eye, as previously described in rabbits [23]. The intraocular injection of MCE, which is a viscoelastic substance that mechanically blocks the aqueous humor outflow, leads to a viscosity-dependent increase in IOP in analogy with what happens in the microbead injection models [22]. Mice were subjected to intraperitoneal avertin anesthesia (0.02 mL of 1.25% avertin/g body weight) and intraocularly injected in both the right and left eye with 5 µL of MCE. Intraocular pressure was measured daily by tonometry.

2.3. Dietary Supplementation

The diet supplement used here (Gangliomix®, marketed by Sooft Italia SpA, Montegiorgio, Italy) is used in humans at the dose of 10 mg/kg (once or twice per day). The mouse dose (125 mg/kg in mice weighing on average 20 g) was calculated by converting the human dose, taking into account the difference in the metabolism of the two species [27]. This dose corresponds to the following doses of the active components: 19.3 mg/kg of dry extract of *Coleus forskohlii* titrated at 10% in forskolin, 14.5 mg/kg of homotaurine, 86.7 mg/kg of a dry extract of spearmint containing 20.9 mg/kg of total polyphenols and 12.6 mg/kg of rosmarinic acid, 2.7 mg/kg of vitamin PP, 0.4 mg/kg of vitamin B2, 0.4 mg/kg of vitamin B6, 0.3 mg/kg of vitamin B1 and 0.5 mg/kg of vitamin B12. The

mouse dose corresponds to a dose in between the minimal and the maximal dose used in humans. Twenty-two mice (11 controls and 11 intraocularly injected with MCE) were orally gavaged once-a-day with 2.5 mg of the diet supplement suspended in 200 μ L of 10% sucrose. An additional 22 mice (11 controls and 11 intraocularly injected with MCE) were orally gavaged once-a-day with 200 μ L of 10% sucrose (vehicle). Control mice were gavaged for 4 weeks. Mice receiving MCE were gavaged for 2 weeks before and 2 weeks after MCE. This regimen was found to preserve retinal function in a mouse model of ONC [20].

Retinal parameters evaluated in the present study (see below) did not differ between the control mice (untreated, fed with vehicle or fed with the diet supplement). In addition, the same parameters did not differ between MCE-injected mice either unfed or fed with vehicle. Results reported below refer to retinal parameters as determined in unfed controls and MCE-injected mice either vehicle-fed or diet supplement-fed.

2.4. Measurement of Intraocular Pressure

IOP was measured by rebound tonometry using an Icare TonoLab instrument (Icare Finland Oy, Helsinki, Finland). Rebound tonometers, which can be used either in anesthetized or conscious rodents, use a magnetic probe that is propelled towards the cornea. The deceleration of the probe after the impact reliably correlates with IOP [28]. To measure IOP, mice were restrained in a home-made soft plastic cone and secured in a restrainer. A few minutes after, IOP was measured from both eyes. Intraocular pressure was determined by averaging 10 consecutive measurements.

2.5. Measurement of Scotopic and Photopic Electrorretinogram

Full-field ERGs were recorded in 6 mice randomly chosen in each group (control mice both unfed and fed with either vehicle or diet supplement for 4 weeks; MCE both unfed and fed with either vehicle or diet supplement for 2 weeks before and 2 weeks after MCE). Recordings were made using silver–silver chloride corneal electrodes after overnight adaptation and a Ganzfeld stimulator (Biomedica Mangoni, Pisa, Italy). Animals were anesthetized with intraperitoneal injection of avertin and pupil dilation was induced in both eyes by instilling a drop of 0.5% atropine. The body temperature was maintained at 38 °C using a homeothermic controller. A needle electrode subcutaneously inserted in the frontal region was used as reference, while a needle electrode subcutaneously inserted at the base of the tail was used as a ground. Retinal responses were collected simultaneously from both eyes using a data acquisition device (Biomedica Mangoni). Recordings were initially taken in the absence of stimuli to measure the background noise levels. Light stimuli were calibrated as luminance energy units in candela seconds per meter squared ($\text{cd}\cdot\text{s}/\text{m}^2$). The scotopic responses, mainly reflecting rod function, were elicited using a 1.00 log $\text{cd}\cdot\text{s}/\text{m}^2$ stimulus, averaging 5 different ERG responses obtained with an interval of 20 s between light flashes. After the acquisition of the scotopic responses, mice were light-adapted for 10 min before recording photopic cone-mediated responses using a 3 $\text{cd}\cdot\text{s}/\text{m}^2$ stimulus on a 30 $\text{cd}\cdot\text{s}/\text{m}^2$ rod-saturating background light. For each mouse, 10 waveforms were recorded with an interstimulus interval of 3 s and averaged. In the photopic ERG, the photopic negative response (PhNR) was identified as the first negative deflection after the b-wave, calculating its amplitude relative to baseline (0 μV).

2.6. Measurement of Pattern Electrorretinogram

PERG responses were evoked in anesthetized mice using an alternating pattern of black and white horizontal bars delivered on a stimulus display unit from a commercially available PERG system (SB700 Advanced, Nikon-Europe, Amsterdam, The Netherlands). Stimuli consisted of 0.05 cycles/deg black and white bars reversing at 1 Hz presented at 98% contrast. The pattern stimuli were administered through a light emitting diode display with a mean luminance of 50 cd/m^2 aligned at about 20 cm from the corneal surface. A total of 200 signals was averaged. The PERG response was evaluated by measuring the amplitude of the N35–P50 and P50–N95 waves (from the trough of the negative peak, N35, to the peak of the positive peak, P50, and from the peak of the

positive peak, P50, to the trough of the negative peak, N95, respectively). The implicit time was determined by measuring the time from the onset of the stimulus to the P50 and N95 peaks.

2.7. Retinal Ganglion Cell Immunohistochemistry and Quantification

Mice under avertin anesthesia ($n = 5$ for each group) were euthanized before removing their eyes. After isolation, retinas were fixed for 90 min at 4 °C in 4% paraformaldehyde in 0.1 M phosphate buffer (PB). Fixed retinas were then stored at 4 °C in 25% sucrose in 0.1 M PB. Retinal ganglion cells were labeled using an antibody against Brn3a (1:100 in PB containing 5% BSA and 2% TritonX-100; sc-6026; Santa Cruz Biotechnology, Santa Cruz, CA, USA) incubating the retinas for 24 h at 4 °C. Retinas were then washed with PB and incubated overnight at 4 °C in an AlexaFluor488-conjugated secondary antibody (1:100; A-16001; Molecular Probes, Eugene, OR, USA). Finally, retinas were washed with PB, mounted on glass slides with the photoreceptor side facing down and viewed with a fluorescence microscope (Ni-E; Nikon-Europe). Images were acquired with DS-Fi1c camera (Nikon-Europe) and Brn3a-positive cells were counted using NIS-Elements software (Nikon-Europe).

2.8. Western Blot

Retinas were separated from enucleated eyes and stored at −80 °C. Six samples for each group, each containing two retinas from two different mice, were used. Retinas were homogenized in RIPA buffer containing phosphatase and proteinase inhibitor cocktails (Roche Applied Science, Indianapolis, IN, USA) and protein concentration was measured with the Micro BCA Protein Assay (Thermo Fisher Scientific, Waltham, MA, USA). Samples (30 µg proteins each) were run on 4%–20% SDS-PAGE gels and proteins were then transferred on polyvinylidene difluoride membranes. Blots were blocked for 1 h with 5% skim milk and incubated overnight at 4 °C with primary antibodies listed in Table S1 using β-actin as the loading control. Blots were then incubated for 1 h with HRP-conjugated secondary antibodies (1:5000) and developed with the Clarity Western enhanced chemiluminescence substrate (Bio-Rad Laboratories, Inc., Hercules, CA, USA). Images were then acquired (ChemiDoc XRS+; Bio-Rad Laboratories, Inc., Hercules, CA, USA). The optical density (OD) of the bands was evaluated (Image Lab 3.0 software; Bio-Rad Laboratories) and data were normalized to the corresponding OD of β-actin or NF-κB as appropriate. All experiments were performed in duplicate.

2.9. Statistical Analysis

Data were analyzed by the Shapiro–Wilk test to verify their normal distribution. Statistical significance was evaluated with Prism 8.0.2 (GraphPad Software, Inc., San Diego, CA, USA) using one-way analysis of variance (ANOVA) followed by Newman–Keuls Multiple Comparison post-hoc test. Data are expressed as means ± SEM of the reported n values. Differences with $p < 0.05$ were considered significant.

3. Results

3.1. Dietary Supplementation Does Not Affect IOP Elevation

As shown in Figure 1, MCE injection in the anterior chamber induced a significant increase in IOP within 24 h from the injection. This is in line with previous findings in rabbits and rats injected with MCE and in mice injected with an MCE derivative, hydroxypropyl MCE [23–25,29]. The IOP increase was maintained for up to two weeks (from 14.3 ± 2.4 to 28.7 ± 0.7 mmHg, $p < 0.001$). In control mice, the vehicle or diet supplement did not affect IOP (not shown). Similarly, IOP elevation was not affected by dietary supplementation for two weeks before and two weeks after intraocular MCE injection.

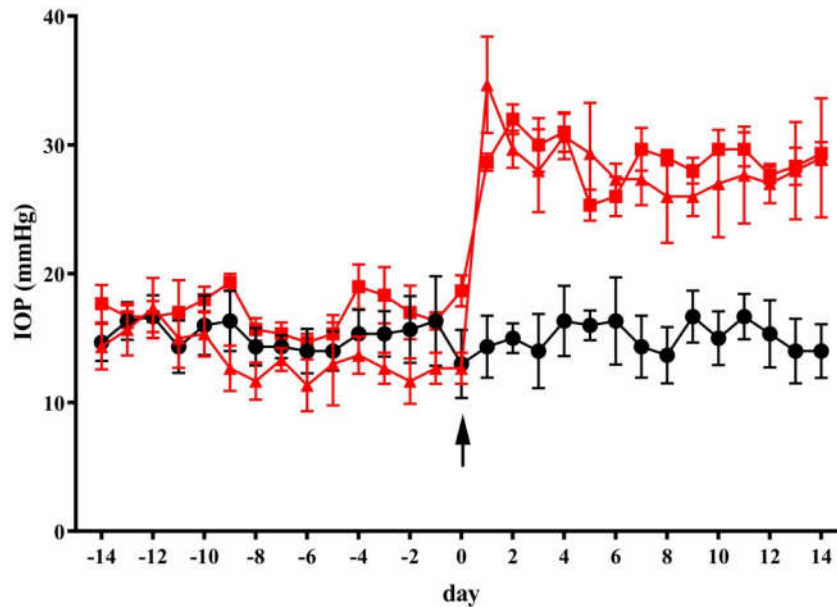


Figure 1. Dietary supplementation did not affect intraocular pressure (IOP). The injection of methylcellulose (MCE) in the anterior chamber at day 0 (arrow) resulted in a significant elevation in the intraocular pressure. Both the vehicle and diet supplement did not affect IOP in mice receiving MCE. Data are shown as mean \pm SEM ($n = 11$ for each group). Black circles and line: control mice; red squares and line: mice intraocularly injected with MCE fed with vehicle; red triangles and line: mice intraocularly injected with MCE fed with diet supplement.

3.2. Dietary Supplementation Prevents the Reduction in PhNR Amplitude

Retinal function was evaluated by measuring the amplitude of different components in both scotopic and photopic full-field ERG, as determined two weeks after intraocular MCE injection. The amplitude of scotopic a- and b-waves as well as the amplitude of the photopic b-wave were used to evaluate outer and mid-retinal function, whereas the amplitude of the PhNR measured in the photopic b-wave was used to evaluate inner retinal function [30]. As shown in Figure 2A–C, in mice fed with vehicle, scotopic a- and b-waves or photopic b-wave did not differ in their amplitudes from those in controls, whereas the amplitude of the PhNR after MCE was reduced by about 45% ($p < 0.001$), a reduction that is in line with previous studies indicating a selective loss of inner retinal function [31,32]. After diet supplementation, the amplitude of the PhNR was about 18% lower than that in controls ($p < 0.01$) and about 40% higher than that in vehicle-fed mice ($p < 0.001$).

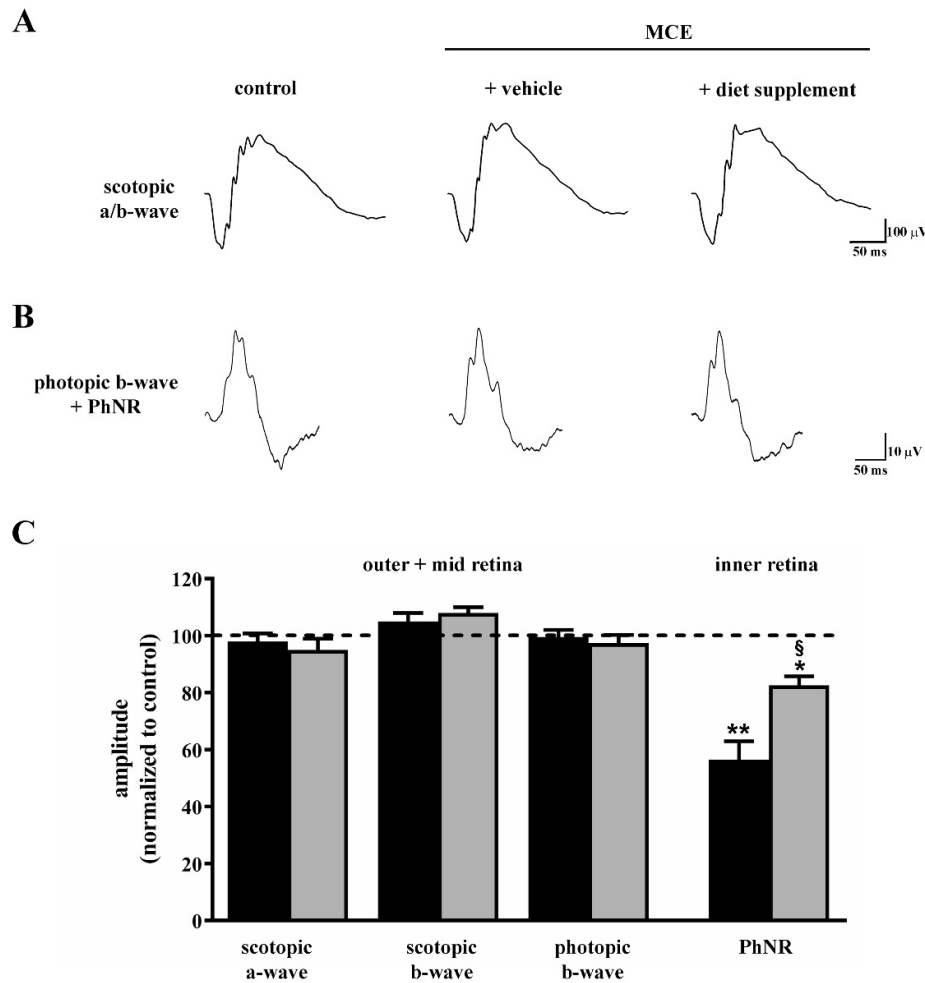


Figure 2. Effects of dietary supplementation on retinal function as evaluated by scotopic and photopic full-field electroretinogram (ERG). Representative ERG traces showing scotopic a- and b-waves (**A**) or photopic b-waves with photopic negative response (PhNR; **B**) in control mice and in mice that received intraocular MCE injection fed with either vehicle or diet supplement. (**C**) Mean amplitudes of ERG responses evaluated as changes from baseline, normalized to the amplitude measured in control mice. MCE did not affect the amplitude of the scotopic a-wave, scotopic b-wave and photopic b-wave, while it reduced the amplitude of PhNR. Dietary supplementation partially prevented the reduction in PhNR amplitude. Data are shown as mean \pm SEM ($n = 6$ for each group). * $p < 0.01$ and ** $p < 0.001$ versus control; § $p < 0.001$ versus MCE mice fed with vehicle (one-way ANOVA followed by the Newman–Keuls multiple comparison post-hoc test). Black bars: mice intraocularly injected with MCE fed with vehicle; grey bars: mice intraocularly injected with MCE fed with diet supplement.

3.3. Dietary Supplementation Prevents the Reduction in PERG Amplitude and Implicit Time

Retinal function was also evaluated by measuring both the amplitude and implicit time of PERG waves two weeks after intraocular MCE injection. As shown by representative PERG waveforms in Figure 3A, MCE injection reduced the PERG amplitude, an effect that was partially prevented by dietary supplementation. In particular, as shown in Figure 3B, in mice fed with vehicle the amplitude of the N35–P50 and the P50–N95 waves was reduced by about 53% and 51% ($p < 0.001$), respectively. In mice receiving the diet supplement, the amplitude of the N35–P50 and P50–N95 waves was reduced by about 22% and 13% ($p < 0.01$), in respect to controls, and was increased by about 40% and 43% ($p < 0.001$), in respect to vehicle-fed mice. In addition, in mice fed with vehicle

the implicit time of the P50 and N95 peaks was increased by about 23% and 16%, respectively ($p < 0.001$), an effect that was abolished by dietary supplementation (Figure 3C).

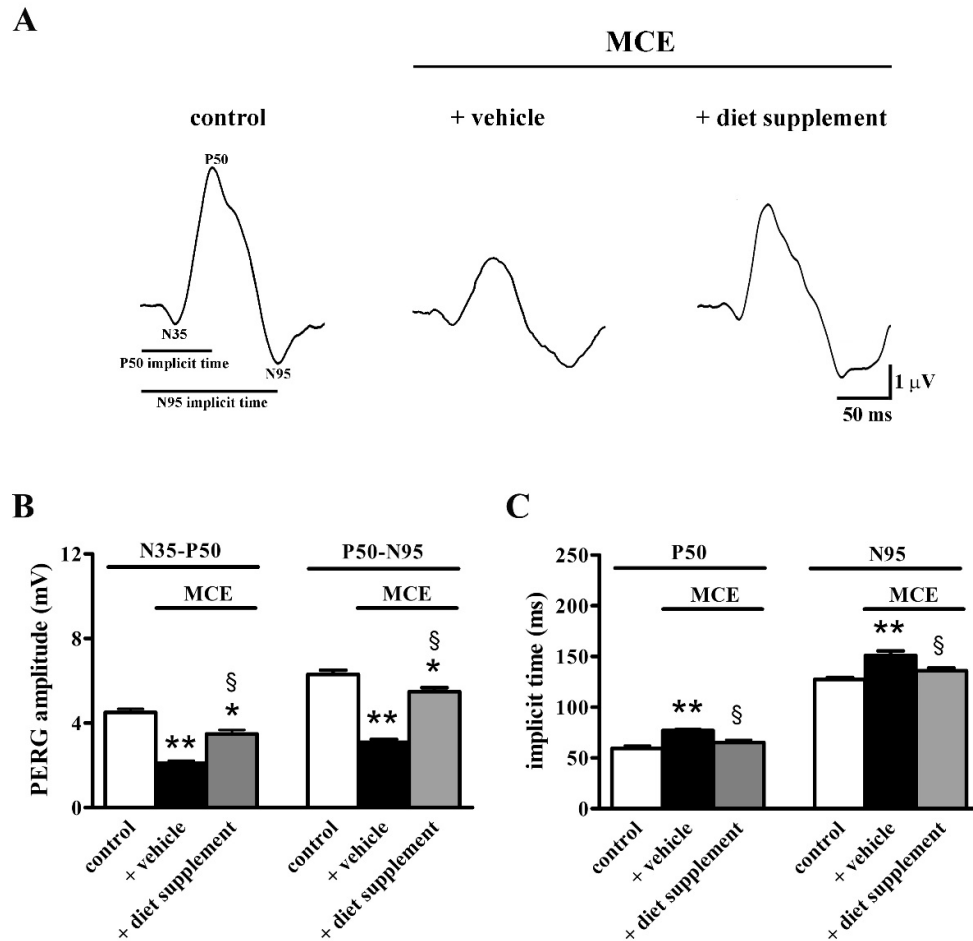


Figure 3. Effects of dietary supplementation on retinal function as evaluated by pattern ERG (PERG). (A) Representative PERG traces showing the two negative peaks (N35 and N95) and the positive peak P50 in control mice and in mice injected with MCE fed with either vehicle or diet supplement. (B) Mean amplitudes of the N35–P50 and P50–N95 waves. MCE reduced the amplitude of both waves, an effect that was partially prevented by dietary supplementation. (C) Mean implicit time of the P50 and N95 peaks was increased by MCE, an effect that was abolished by dietary supplementation. Data are shown as mean \pm SEM ($n = 6$ for each group). * $p < 0.01$ and ** $p < 0.001$ versus control; § $p < 0.001$ versus MCE mice fed with vehicle (one-way ANOVA followed by the Newman–Keuls multiple comparison post-hoc test).

3.4. Dietary Supplementation Prevents RGC Death

In the MCE model, the increased IOP is paralleled by a massive RGC death [24]. We examined whether improved retinal function was accompanied by a reduced RGC loss. As depicted in Figure 4A–C, the immunostaining for the RGC marker Brn3a shows that in mice fed with vehicle, intraocular MCE injection resulted in a significant RGC loss without any apparent regional difference. The diet supplement partially prevented RGC death, as also confirmed by the high magnification pictures in Figure 4D–F. The effectiveness of the diet supplement in sparing RGCs was demonstrated by RGC quantification (Figure 4G). MCE reduced the RGC number by about 41% ($p < 0.001$) in vehicle-fed mice, while diet supplementation spared RGCs by about 20% ($p < 0.001$). Both the reduction in RGC number and its sparing did not display any retinal regionality (Table 1).

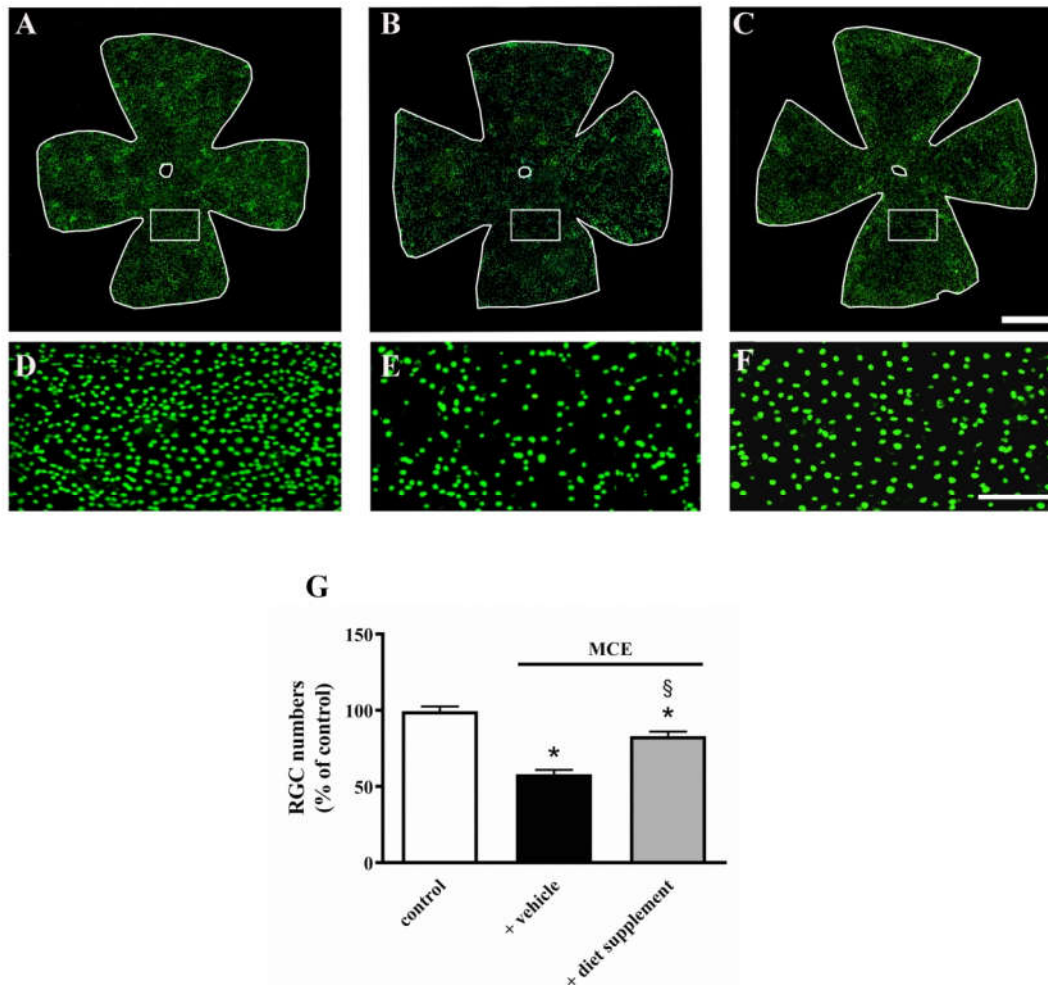


Figure 4. Effects of dietary supplementation on retinal ganglion cell (RGC) number. (A–C) Representative images of retinal whole mounts immunostained for brain-specific homeobox/POU domain protein 3A (Brn3a) in control mice (A) and in mice that received MCE either fed with either vehicle (B) or diet supplement (C) ($n = 5$ for each experimental group). (D–F) High magnification of the boxed areas in A–C. Scale bars: 1 mm (A–C) or 250 μ m (D–F). (G) A count of Brn3a-labeled RGCs. MCE reduced RGC number, an effect that was partially prevented by dietary supplementation. Data are shown as mean \pm SEM ($n = 5$ for each group). * $p < 0.001$ versus control; § $p < 0.001$ versus MCE mice fed with vehicle (one-way ANOVA followed by the Newman–Keuls multiple comparison post-hoc test).

Table 1. Effect of dietary supplementation on RGC number in peripheral and midperipheral retina.

	RGC Number (% of Control)	
	Peripheral	Midperipheral
Control	100 \pm 9	100 \pm 7
MCE + vehicle	53 \pm 7 *	58 \pm 6 *
MCE + diet	77 \pm 8 *§	84 \pm 11 *§

Data are shown as mean \pm SEM ($n = 5$ for each group). * $p < 0.001$ versus control; § $p < 0.001$ versus MCE mice fed with vehicle (one-way ANOVA followed by the Newman–Keuls multiple comparison post-hoc test). The RGC number in the peripheral and midperipheral retina was 9170 \pm 825 and 12240 \pm 857, respectively, in agreement with previous findings [33].

3.5. Dietary Supplementation Prevents Inflammation and Apoptosis

In glaucoma, glial activation triggers major inflammatory processes [34]. As shown in Figure 5, in the MCE model supplemented with vehicle Western blot analysis revealed drastically increased levels of both ionized calcium binding adaptor molecule 1 (Iba1) and glial fibrillary acidic protein (GFAP), markers of microglia and Müller cell activation, respectively. In particular, the Iba1 levels were increased by about 2.7-fold, while the GFAP levels were increased by about 3.2-fold ($p < 0.001$). Dietary supplementation prevented upregulated levels of both Iba1 and GFAP that were similar to those determined in controls.

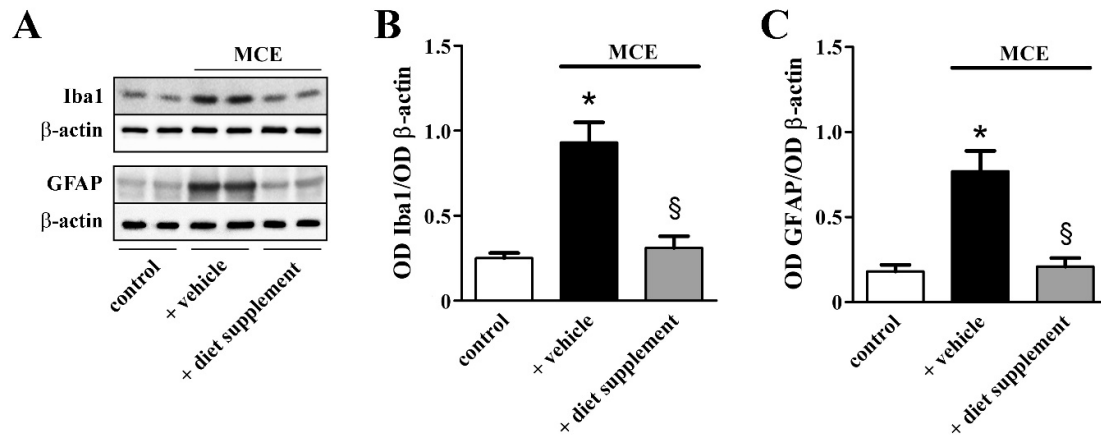


Figure 5. Effects of dietary supplementation on glial activation. (A) Representative Western blots from retinal homogenates of control mice or mice that received MCE fed with either vehicle or diet supplement. (B,C) Densitometric analysis of ionized calcium binding adaptor molecule 1 (Iba1; B) or glial fibrillary acidic protein (GFAP; C) levels. MCE resulted in increased levels of both Iba1 and GFAP. Dietary supplementation prevented the upregulation of Iba1 and GFAP ($n = 6$ for each group). * $p < 0.001$ versus control; \S $p < 0.001$ versus MCE mice fed with vehicle (one-way ANOVA followed by the Newman–Keuls multiple comparison post-hoc test).

As shown in Figure 6, downstream to glial activation, inflammatory markers including the phosphorylated form of the nuclear factor kappa-light-chain-enhancer of activated B cells (NF- κ B), the pro-inflammatory cytokines tumor necrosis factor (TNF)- α and interleukin (IL)-6 were drastically upregulated while the level of the anti-inflammatory cytokine IL-10 was decreased. In particular, the levels of NF- κ B phosphorylation, TNF- α and IL-6 were increased by about 4.6-, 2.7- and 1.4-fold ($p < 0.001$, $p < 0.01$ and $p < 0.001$, respectively), while IL-10 levels were decreased by about 3.3-fold ($p < 0.001$). The protein expression of inflammatory markers almost recovered to their control levels after dietary supplementation.

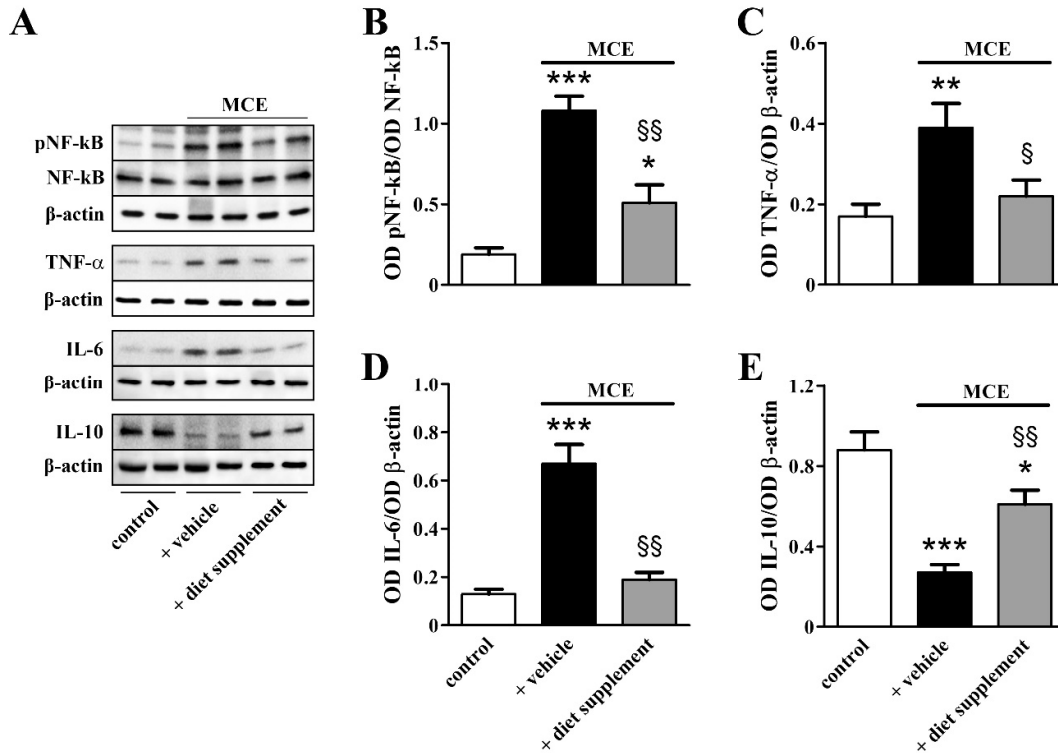


Figure 6. Effects of dietary supplementation on inflammatory markers. (A) Representative Western blots from retinal homogenates of control mice or mice that received MCE fed with either vehicle or diet supplement. (B–E) Densitometric analysis of the levels of phosphorylated form of nuclear factor kappa-light-chain-enhancer of activated B cells (NF-kB), tumor necrosis factor (TNF)- α , interleukin (IL)-6 and IL-10. MCE resulted in increased levels of the phosphorylated form of NF-kB, TNF- α and IL-6, while IL-10 levels were decreased, effects that were almost completely prevented by dietary supplementation ($n = 6$ for each group). * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$ versus control; § $p < 0.05$ and §§ $p < 0.001$ versus MCE mice fed with vehicle (one-way ANOVA followed by the Newman–Keuls multiple comparison post-hoc test).

Whether the efficacy of dietary supplementation on sparing RGCs might involve the counteraction of apoptotic processes was evaluated by measuring the protein level of well-established markers in the apoptotic cascade. As shown in Figure 7, the MCE model was characterized by increased Bax/Bcl2 ratio (about 5.1-fold, $p < 0.001$) with upregulated levels of the pro-apoptotic Bax and unaltered levels of the anti-apoptotic Bcl2. Downstream to increased Bax/Bcl2 ratio, levels of the active (cleaved) form of caspase 3, the major apoptosis-associated effector caspase, were increased by about 8.5-fold ($p < 0.001$). Bax/Bcl2 ratio and caspase-3 activation almost recovered to their control levels after dietary supplementation.

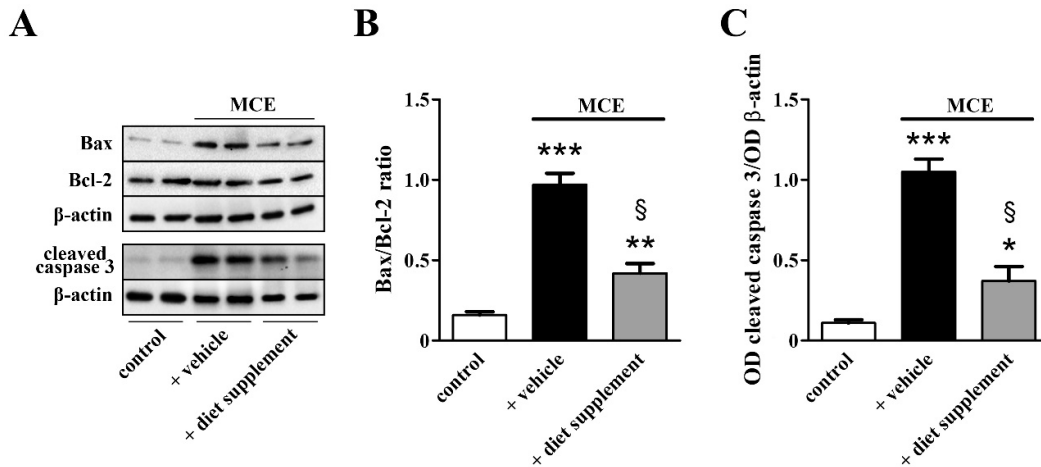


Figure 7. Effects of dietary supplementation on apoptotic markers. (A) Representative Western blots from retinal homogenates of control mice or mice that received MCE fed with either vehicle or diet supplement. (B,C) Densitometric analysis of the levels of Bax/Bcl-2 (B) and active caspase 3 (C). MCE resulted in increased levels of both Bax and active caspase 3 without altering Bcl-2 levels. Dietary supplementation prevented the upregulation of both Bax and the active form of caspase 3 ($n = 6$ for each group). * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$ versus control; § $p < 0.001$ versus MCE mice fed with vehicle (one-way ANOVA followed by the Newman–Keuls multiple comparison post-hoc test).

4. Discussion

Glaucoma is usually controlled with medication and/or surgery. Although not free of side effects, first line medication includes eye drops that lower IOP by reducing the amount of aqueous humor production or allowing its better drainage [10]. The impact of diet on eye health has recently become of rapidly increasing interest for ocular pathologies and evidence is mounting that bioactive antioxidant/anti-inflammatory agents may provide the first line of biological defense against oxidative stress/inflammation. In particular, there is extensive literature demonstrating the efficacy of nutritional products against retinal cell loss of which inflammatory processes are the major triggers [15,16]. In particular, some nutrients have been proven to be capable of increasing circulation to the optic nerve, modulating excitotoxicity and promoting RGC survival [19]. In some instances, nutrients exert a hypotonizing effect on IOP as in the case of polyunsaturated fatty acids that effectively lower IOP both in glaucoma patients and in animal models [15]. However, the lack of clinical trials may limit their current therapeutic use.

In the present study, we mimicked IOP elevation that characterizes hypertensive glaucoma by injecting the anterior chamber of the mouse eye with MCE. MCE is a molecule that causes a viscosity-dependent ocular hypertension by blocking the trabecular meshwork and preventing the outflow of the aqueous humor [23]. The MCE model in the rat is characterized by an early elevation of IOP that, after a return to its basal level, is followed by a second peak, thus reaching a steady state that remains stable for at least two weeks [24,29]. This is in line with additional models in which IOP elevation has been obtained through the blockade of the trabecular meshwork (see for instance [35]). The MCE model has been recently used to demonstrate the hypotensive efficacy of topical nanomicellar formulations of melatonin and agomelatine in the rat eye [29]. In respect to additional models that mimic the human acute angle-closure glaucoma, for instance the ischemia/reperfusion model characterized by a transient acute IOP elevation [36], the prolonged IOP elevation of the MCE model more closely simulates the human hypertensive glaucoma.

The role of apoptosis in glaucomatous degeneration has become a research focus to address the mechanisms underlying RGC loss [37]. In the rat, apoptotic death of RGCs starts seven days after MCE injection [24], thus rendering the MCE model suitable for studying the effects of treatments intended to counteract RGC degeneration and its morpho-functional/biomolecular correlates. As

shown by the present results, MCE-induced IOP elevation is coupled to a defective ratio of Bax/Bcl2 and the increased expression of the apoptosis effector caspase-3. The activation of the apoptotic cascade is paralleled by RGC loss as determined by a drastic decrease in immunostaining with Brn3a, a transcription factor highly expressed in the developing peripheral sensory nervous system, which is a well-established marker for RGCs [26]. This is in line with previous findings demonstrating that in rodent models in which trabecular meshwork blockade leads to IOP elevation, apoptotic RGC loss follows IOP, rising a while after [38–40].

As a consequence of RGC death, both PhNR and PERG are reduced in amplitude in line with previous reports. For instance, reduced PERG amplitude has been detected in DBA/2J mice, a strain that develops spontaneous age-dependent IOP elevation followed by RGC death [41], while reduced amplitude of PhNR appears to be coupled to RGC death in a mouse model of ONC [20]. Significant positive correlation of RGC loss rate with PhNR amplitude decline was found to take place at different times depending on the glaucomatous rat model [42]. In humans, both PhNR and PERG have demonstrated their feasibility as useful and sensitive tests to assess early RGC loss in glaucoma patients [43], although electroretinographic measurements do not always correlate with structural changes (actually, they might precede detectable structural modifications) [44]. As also shown here, both PhNR and PERG are equally affected in the MCE model and their reduced amplitude is coupled to homogeneously dispersed RGC loss. This is in line with the fact that PhNR originates from peripherally located RGCs, while PERG originates from centrally located RGCs [43]. No regional differences in RGC loss have been observed in either the retina or the RGC axons of DBA/2J mice [45], while major RGC loss in the peripheral retina has been detected after microbead injection into the mouse anterior chamber [35]. In this line, the susceptibility of RGCs to ONC has been found to depend on RGC types [46].

Apoptotic death of RGCs occurs as a consequence of a plethora of pathological events of which neuroinflammation is a major contributor [47]. Müller cells and microglia, together with astrocytes, represent the three populations of retinal glial cells that, in glaucomatous eyes, become reactive, proliferate and release inflammatory mediators [34]. As shown here, IOP elevation due to MCE injection activates an inflammatory cascade triggered by glial cell activation as determined by upregulated levels of both Iba-1, a marker of activated microglia, and GFAP, a marker of Müller cell gliosis. Downstream to their activation, glial cells trigger NF- κ B that enters the nucleus and leads to the transcription of inflammatory cytokines including IL-6 and TNF- α , in line with previous findings in a rat model of ONC [48]. In turn, TNF- α upregulation exacerbates the inflammatory processes by increasing NF- κ B activation, thus generating a positive feed-back loop. As also shown here, the anti-inflammatory cytokine IL-10 is downregulated, thus indicating that the retinal inflammatory milieu is likely due to an imbalance in the production of both pro- and anti-inflammatory mediators. This is in agreement with a recent study demonstrating a reduced level of IL-10 in the aqueous humor of glaucoma patients in respect to controls [49].

Whether inflammation participates to RGC loss or acts as a protective mechanism to promote RGC survival is still matter of debate [47]. The activation of inflammatory processes may indeed be protective in the early phase of glaucoma, but a sustained production of inflammatory mediators may shift the physiological balance between beneficial and harmful effects of inflammation toward a pro-inflammatory environment, thus affecting RGC survival and driving the progression of neurodegeneration [50]. This double-face of biological processes is not an exclusive feature of inflammation as it has been also reported for other processes as, for instance, autophagy [51] or oxidative stress [52].

As demonstrated by the present findings, dietary supplementation results in a reduced inflammatory cascade that is coupled to an improved ratio of Bax/Bcl2 and a decreased expression of the apoptosis effector caspase-3, indicating that the diet supplement may prevent RGC death by blocking early events in the apoptotic cascade. This is in agreement with previous findings demonstrating that supplementing the diet with natural compounds reduces both the severity of inflammation and the apoptotic flux, thus sparing RGCs from death [15]. In this line, the flavonoid hesperidin has been shown to suppress both inflammation and upregulated calpain, an enzyme

leading to the activation of apoptotic processes, thereby sparing RGCs from death and ameliorating visual function in a mouse model of N-methyl-D-aspartate (NMDA) receptor-induced retinal injury [53]. Similarly to flavonoids, the most abundant opioid found in *Papaver somniferum*, morphine, inhibits the production of inflammatory cytokines thus resulting in reduced expression of apoptotic markers, RGC rescue and improved PERG in a rat model of glaucoma [54]. As shown here, downstream to the recovered apoptotic cascade RGCs are spared by more than 50% in line with previous results in the ONC model [20]. Comparable RGC rescue has been determined after diet supplements based on forskolin alone or in association with homotaurine and carnitine in a rat model of transient acute IOP elevation [36].

The bioactive molecules used here have well known neuroprotective properties when administered alone or in combination with either each other or anti-hypertensive drugs. In glaucoma models, forskolin acts synergistically with homotaurine to prevent the apoptotic cascade triggered by IOP elevation thus leading to RGC rescue [36]. In addition, forskolin, when administered in combination with classical anti-hypertensive drugs, not only reduces IOP well beyond the levels achieved with traditional therapy alone [55,56], but also exerts direct neuroprotective efficacy by limiting excitotoxic damage and activating neurotrophic mechanisms [16]. In glaucoma patients in which IOP elevation has been compensated by traditional therapy, dietary supplementation with forskolin, homotaurine and B vitamins ameliorates RGC dysfunction, indicating a possible synergy between the different bioactive components [57]. Among the other constituents of the diet supplement, the spearmint extract is rich in polyphenols of which flavonoids exert neuroprotective effects on RGC loss through reduced inflammation and oxidative stress [15], although no significant efficacy of flavonoids on IOP elevation has been demonstrated in glaucoma patients [58]. Both homotaurine and group B vitamins have well known neuroprotective efficacy [15,59,60] and, in particular, vitamins are good candidates against glaucoma because of their well-established antioxidant properties [61]. Among vitamins, the neuroprotective efficacy of vitamin B1 against RGC death has been determined [62] and its deficiency has been associated to an increased risk of developing glaucoma [63]. On the other hand, an association between vitamin levels in the serum and glaucoma prevalence in humans is still a matter of debate [15].

As also shown by the present results, dietary supplementation triggers an ameliorative cascade that does not appear to depend on IOP reduction, suggesting that non-IOP-related mechanisms of action may be activated by the compound. In this line, IOP-decreasing therapies are not always able to prevent the progression of glaucoma and the neuroprotective efficacy of nutritional compounds has been demonstrated in glaucoma patients irrespective of their efficacy in lowering IOP [64,65]. In addition, neuroprotective compounds are effective in reducing RGC degeneration although not in affecting IOP elevation in glaucoma models [39,54,66]. In fact, IOP-independent mechanisms may contribute to RGC death including oxidative stress, excitotoxicity, neuroinflammation and impaired ocular blood flow [67]. On the other hand, the relationship between IOP increases and RGC degeneration remains to be clarified. For instance, pressure levels of 25 mmHg have been recently reported as the threshold above which RGCs begin to degenerate [68], while IOP higher than 21/22 mmHg has been generally reported as a critical level.

As demonstrated here, RGC survival is reflected at the functional level by the preserved amplitude of both PhNR and PERG that likely indicates the restored retinal dysfunction, although visual sparing is difficult to evaluate by standard electrophysiological testing [69]. This is in line with previous evidence of restored retinal loss after dietary supplementation. For instance, the diet supplement used here prevents the PhNR amplitude reduction in a mouse model of ONC [20], while quercetin reverses the decrease in PhNR amplitude in a rat model of chronic glaucoma [70]. In addition, vitamin B3 prevents glaucoma in aged mice by supporting mitochondrial metabolism [71]. Moreover, additional compounds, such as neurotrophins and delta opioid agonists, may prevent PERG alterations in rodent models of elevated IOP [72,73].

5. Conclusions

The final purpose of the present study would be to expand the therapeutic armamentarium against glaucoma and to compensate, if possible, the faults of the traditional therapy by an attempt to bridge the gap between preclinical approaches and clinical studies. Confirming in a model of increased IOP the efficacy of a diet supplement previously used with success in a model of acute retinal damage further strengthens the possibility to extrapolate to humans the findings obtained in animal models. With the due caution, the stringency of the mouse model used here to human glaucoma supports the translatability of the present results to clinical settings. The fact that the components of the diet supplement may act independently of their efficacy on IOP lowering indicates that, overall, the association of the different compounds exerts a direct neuroprotective effect. Thus, the diet supplement used in the present study may be viewed as a potential remedy to be added to the currently approved drug therapies for improving RGC protection. The schematic diagram of Figure 8 summarizes the cascade of events leading to major neuroprotective efficacy of the diet supplement on RGCs at the morpho-functional/biomolecular level.

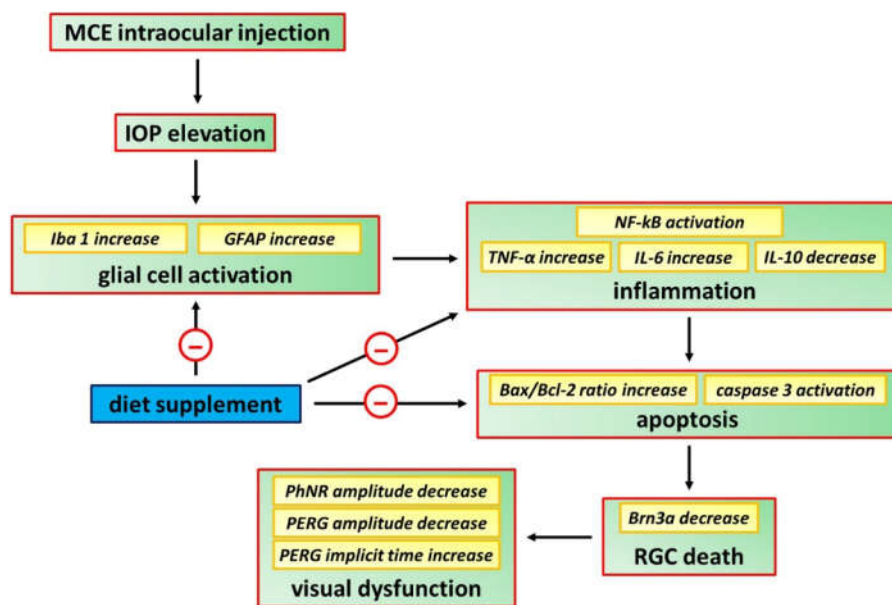


Figure 8. Schematic diagram showing possible mechanisms through which the diet supplement counteracts RGC death thus preserving, at least in part, retinal function. MCE leads to IOP elevation that, in turn, generates a downstream cascade that, through the induction of gliosis and inflammation, triggers RGC degeneration by apoptosis and visual dysfunction. The diet supplement, acting as a direct neuroprotectant, reduces gliosis, inflammation and apoptotic processes thus sparing RGCs from death and counteracting visual dysfunction.

Supplementary Materials: The following are available online at www.mdpi.com/2072-6643/12/4/1189/s1, Table S1: List of antibodies used in Western blot.

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