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Effects of blue light exposure on the retina of mice

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Article

Keywords: Oxidative stress, Visual system, Antioxidant defense system, Artificial light, Photoprotector, Mouse model

Posted Date: November 4th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11037526/v1

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Additional Declarations: No competing interests reported.

Abstract

Blue light, a high-energy component of the visible spectrum, has drawn attention because of the intensive use of electronic devices with LED screens. This wavelength, upon penetrating ocular structures such as the cornea, lens, and retina, can induce the formation of reactive oxygen species (ROS), promote oxidative stress, and compromise cellular integrity. In this study, 25 mice (*Mus musculus* – C57BL/6J Unib) were exposed to blue light (32–78 lux) during the nighttime period, from 7 p.m. to 7 a.m., for 21 days, and divided into five experimental groups (n = 5). The control group was maintained under ambient light, whereas the other groups were exposed to blue light, with or without a photoprotective filter, for 2 or 12 hours daily. The retina was evaluated for oxidative status and histological alterations. The results revealed a significant increase ($p < 0.05$) in ROS production after 2 hours of exposure, accompanied by a reduction in ACAP and CAT levels, as well as a decrease in lipid peroxidation (LPO). Histological analyses revealed no structural ($p > 0.05$) or pathological alterations in the retinal layers. The tested photoprotective agent demonstrated the potential to mitigate the effects of blue light. Although exposure to blue light at levels that simulate everyday conditions induces oxidative stress, retinal antioxidant defenses are effective in preventing damage.

Highlights

- Exposure to blue light triggers an increase in ROS production.

- Blue light decreases ACAP levels.

- The photoprotective filter was effective in minimizing the deleterious effects of blue light exposure.

1. Introduction

Blue light is a portion of visible light characterized by short wavelengths ranging from 425 to 500 nm and, consequently, high energy. Prolonged exposure to blue light at night, particularly from electronic device screens, can lead to negative health effects. This wavelength suppresses the production of melatonin, the hormone responsible for inducing sleep, which can cause sleep disturbances and affect overall well-being. Beyond its systemic impacts, blue light directly affects the visual system. Because its wavelengths align with the absorption range of retinal photoreceptors, this light possesses high ocular penetration capacity, thereby rendering retinal tissue vulnerable to damage. [1].

Blue light stimulates the formation of reactive oxygen species (ROS), unstable molecules that promote oxidative stress and compromise cellular integrity [7, 8]. This process may result in loss of cellular functionality [9] and in the development of ocular pathologies [10]. These conditions are directly associated with oxidative stress, which is classically defined as an imbalance between the pro-oxidant and antioxidant systems or as alterations in the redox state and cellular signaling [11, 12]. Biological systems, which are composed of both enzymatic and nonenzymatic antioxidants, have developed robust antioxidant defense mechanisms to counteract ROS. When these systems fail or become overloaded,

ROS react with biomolecules, causing significant oxidative damage, manifested through protein carbonylation, DNA oxidation, and lipid peroxidation (LPO) [13, 14, 15].

One of the main modern threats to ocular health is excessive screen exposure time. To mitigate this problem, protective lenses have emerged, which are designed to filter part of the blue light emitted by electronic devices and other sources, with the aim of reducing discomfort and preserving visual acuity [16]. However, recent research on the effectiveness of these lenses has demonstrated that the protection they offer is not clinically relevant. A study by [17], for example, revealed that the use of these filters did not reduce the incidence of blue light in the progression of macular atrophy. Although in vitro studies indicate that such filters may influence the viability, metabolic activity, and morphology of retinal pigment epithelium cells [18, 19], clinical trials have not reported statistically significant differences in the development of AMD in patients treated with these lenses [19, 20, 21].

Considering the still limited understanding of the effects of blue light on the visual system, it is important to emphasize that scientific literature consistently demonstrates that this radiation is capable of inducing ROS production and causing ocular damage [22, 23, 24, 25, 26]. On the basis of these findings, the biological effects of blue light cannot be analyzed in isolation, as blue light is directly linked to contemporary lifestyles and the intensive use of digital technologies, which have resulted in a significant increase in screen exposure time, a phenomenon that intensified during the COVID-19 pandemic. The importance of this issue is highlighted by the global average screen time, which is estimated at approximately 6 hours and 40 minutes per day [27].

This harmful interaction is particularly relevant in the retina, as blue light reaches photoreceptor cells, which absorb photons and initiate a cascade of biochemical reactions responsible for visual perception [9, 28]. However, the effects of this radiation at illuminance levels that simulate normal ambient light (approximately 100 lux) remain poorly understood [29]. This limitation arises because many studies use high light intensities (above 400 lux and up to 2,000 lux), which do not accurately reflect how the human visual system behaves under real-world exposure to blue light [3, 30, 31, 32, 33, 34]. Another relevant issue is the use of limiting biological models, such as albino animals, which do not accurately reproduce everyday exposure conditions since they exhibit greater ocular transparency, increasing the amount of electromagnetic radiation reaching the retina [35, 36, 37].

Given these knowledge gaps and the continuous exposure to blue light, investigating the physiological effects of blue light on the visual system is essential. This research represents a significant advancement, providing fundamental insights into the impact of low-irradiance blue light exposure. The knowledge obtained from pigmented murine models is crucial for driving the development of future technological innovations aimed at establishing safe exposure limits and at protecting and restoring ocular health, thereby contributing broadly to the promotion of visual well-being.

2. Methods

The experimental procedures used in the present study were based on the protocol previously described by Lanius *et al.* [38]. The experimental conditions and analytical procedures were maintained as described below to ensure methodological comparability, while the procedures relevant to the present study are detailed in the following sections.

2.1 Animals and housing conditions

Twenty-five male C57BL/6J Unib mice (*Mus musculus*) were used in the experiments. The animals were isogenic, with dark eyes and fur, and were 37–51 days old at the beginning of the experimental period. The animals were obtained from the Center for Experimental Biological Models (CeMBE), Pontifical Catholic University of Rio Grande do Sul (PUC/RS), Brazil.

Upon arrival, the animals were housed for 15 days in the Sectorial Animal Facility of the Faculty of Medicine, Federal University of Rio Grande (FaMed/FURG). The mice were maintained in ventilated racks under controlled environmental conditions, with a temperature of 20 ± 2°C, relative humidity of 40–60%, and a 12 h light/12 h dark cycle. Standard laboratory chow and water were provided *ad libitum* throughout the acclimatization and experimental periods.

All experimental procedures involving animals were conducted in accordance with the guidelines established by the Commission for Ethics in the Use of Animals of the Federal University of Rio Grande (CEUA-FURG) and were approved under protocol number P024/2022.

2.2 Experimental design and blue-light exposure

Following acclimatization, the animals were randomly allocated to five experimental groups (n = 5 per group). The control group (CTR) was maintained under the laboratory's ambient lighting conditions, corresponding to a 12 h light/12 h dark cycle, without exposure to light emitted by the experimental electronic device.

The remaining groups were subjected to blue-light exposure under different exposure durations and optical-filter conditions. Group 2 (2h/N) was exposed to blue light for 2 h without the blue-light filtering lens, whereas Group 3 (12h/N) was exposed to blue light for 12 h under the same unfiltered condition. Group 4 (2h/W) received 2 h of blue-light exposure with the blue-light filtering lens, while Group 5 (12h/W) received 12 h of blue-light exposure with the same protective lens.

Blue-light exposure was performed for 21 consecutive days, beginning at 19:00 h. The exposure system was adapted from the previously published methodology [38]. Mice assigned to the exposure groups were individually housed in isolated acrylic compartments positioned within a ventilated rack. Blue light was generated using monochromatic LED lamps (OSRAM LED CLASSIC A60 RGB, 7.5 W, 1/EA 1/R 1/R.C.). The lamps were operated at the minimum intensity, corresponding to 32–78 lux, and positioned at the front of the acrylic compartments to provide horizontal illumination of the animals' eyes.

To minimize unintended light exposure between experimental groups, the racks were manually covered with opaque *blackout* material before each exposure session. The covers were removed immediately after the exposure period. In the 12-h exposure groups, the LED lamps were switched on and off manually. In the 2-h exposure groups, light exposure was controlled automatically using a timer.

For the filtered exposure conditions, ophthalmic lenses containing a blue-light filtering coating were used. The lenses were manufactured using VARILUX® Lens Technology (Essential Blue series) and positioned over the light source, with a circumference corresponding to that of the upper portion of the blue-light-emitting lamp.

2.3 Tissue collection

At the end of the 21-day exposure period, the animals were euthanized by intraperitoneal administration of ketamine (100 mg/kg) and xylazine (10 mg/kg). Both eyes were subsequently enucleated, and ocular tissues were collected for biochemical and histological analyses.

The retina from the left eye and the right ocular globe of each animal were processed immediately after euthanasia for the determination of reactive oxygen species (ROS) and histological assessment, respectively. Retinal tissue obtained from the right eye was stored under refrigerated conditions for subsequent analyses of antioxidant capacity against peroxyl radicals (ACAP), catalase activity (CAT), and lipid peroxidation (LPO).

2.4 ROS determination

ROS production was quantified using the method previously described [39]. Briefly, 2',7'-dichlorofluorescein diacetate (H_2DCF-DA; Molecular Probes, USA) was used as a fluorescent probe. Following oxidation by ROS and hydrolysis by esterases, H_2DCF-DA generates a fluorescent product that is excited at 480 nm and detected at 525 nm.

Fluorescence measurements were performed in microplates using a fluorimeter (Victor 2 Perkin, USA). Fluorescence was recorded at 5-min intervals over a total period of 120 min. Total fluorescence was estimated by integrating fluorescence units (FU) over the measurement period after fitting the fluorescence data to a second-order polynomial function. ROS levels were normalized according to the protein content of each biological sample and expressed as FU mg protein^{-1}.

2.5 Antioxidant capacity against peroxyl radicals

Antioxidant capacity against peroxyl radicals (ACAP) was assessed according to the method described by [40]. Retinal samples were weighed, homogenized, and centrifuged, and the resulting supernatants were used for the analysis.

The oxidative challenge was generated using 2,2'-azobis(2-methylpropionamidine) (ABAP), while H_2DCF-DA was used as the fluorescent probe for ROS production. Fluorescence was monitored for 60 min in microplates using a fluorimeter (Victor 2 Perkin, USA).

The assay is based on the thermal decomposition of ABAP, which produces peroxyl radicals capable of oxidizing H_2DCF-DA and generating the fluorescent product detected at 525 nm following excitation at 480 nm. Total fluorescence was calculated by integrating FU over the measurement period after fitting the fluorescence data to a second-order polynomial function.

ACAP was determined from the difference between the integrated fluorescence areas obtained in the presence and absence of ABAP. Values were normalized according to the protein concentration of each sample, following the calculation described in [40].

2.6 Catalase activity

Catalase (CAT; EC 1.11.1.6) activity was determined according to the method described by [41]. The assay was based on the rate of hydrogen peroxide (H_2O_2) degradation per minute. Enzymatic activity was expressed in CAT units, with one unit corresponding to the amount of enzyme required to hydrolyze 1 µmol of H_2O_2 per minute per milligram of protein at 25°C and pH 8.0.

Measurements were performed using a digital spectrophotometer.

2.7 Lipid peroxidation

Lipid peroxidation (LPO) was quantified using the FOX assay according to the methodology described in [42, 43]. This method is based on the oxidation of Fe(II) by lipid hydroperoxides and other FOX-reactive substances under acidic conditions in the presence of xylenol orange, which forms a complex with Fe(III).

Absorbance was measured at 550 nm using a microplate reader. Cumene hydroperoxide (CHP; Sigma) was used as the analytical standard. LPO levels were expressed as nanomoles of CHP equivalents per gram of wet tissue (nmol CHP g^{-1} wet tissue).

2.8 Histological analysis

For histological assessment, one ocular globe from each animal was collected immediately after euthanasia and fixed in 4% paraformaldehyde for 8 h in 0.1 M phosphate-buffered saline (PBS). The tissues were subsequently dehydrated through a graded ethanol series, cleared in xylene, and embedded in Paraplast® using an automated tissue processor (Leica ASP 200S).

The paraffin-embedded samples were sectioned at a thickness of 6 µm using a microtome (Leica RM2255). Tissue sections were stained with hematoxylin and eosin and examined using an Olympus BX51 microscope equipped with a DP72 digital camera.

Corneal integrity and thickness were evaluated using ImageJ software. Retinal morphology was assessed by measuring the thickness of the following retinal layers: retinal pigment epithelium (RPE), photoreceptor layer (PH), outer nuclear layer (CNL), outer plexiform layer (EP), inner nuclear layer (IN), inner plexiform layer (IP), ganglion cell layer (GC), and optic nerve fiber layer (ONF).

2.9 Statistical analysis

Statistical analyses were performed using one-way analysis of variance (ANOVA), followed by the Newman–Keuls post hoc test. Statistical significance was set at $p < 0.05$. Data were expressed as means with the corresponding standard error.

3. Results

3.1 ROS production

Blue light caused an increase ($p < 0.05$) in ROS production levels in the retinas of animals exposed for 2 hours, both in those without photoprotection and in those with photoprotection (Fig. 1). However, animals that were exposed for 12 hours did not significantly differ from those in the control group ($p > 0.05$).

3.2 ACAP

Exposure to blue light resulted in a reduction in ACAP activity in the retinas of the mice. All groups of animals exposed for 2 and 12 hours, both with and without protective filters, presented significantly lower ACAP activity ($p < 0.05$) than did the control group (Fig. 2).

3.3 CAT activity

Compared with that in the control group, exposure to blue light resulted in a reduction in catalase activity in the group exposed for 12 hours to a protective filter ($p < 0.05$). The other groups did not significantly differ from the control group (Fig. 3).

3.4 LPO levels

Exposure to blue light resulted in a decrease ($p < 0.05$) in LPO levels in the retinas of animals exposed for 2 hours without a protective filter. In addition, a decrease in LPO levels was observed in animals exposed to a protective filter for 12 hours compared with those in the control group. The other groups did not significantly differ from the control group (Fig. 4).

3.5 Histological analysis

No significant morphological differences were observed in the thickness of the retinal layers in any of the groups exposed to blue light, with or without a filter, compared with the control group ($p > 0.05$) (Fig. 5). Furthermore, no structural or morphological alterations indicative of pathological conditions were observed in the retinas of the animals exposed to blue light.

4. Discussion

In this study, we demonstrated that chronic exposure to blue light at intensities mimicking those received by humans during the use of electronic devices, induced significant alterations in the retinal

oxidative status of mice. These alterations are characterized by dysfunction in the antioxidant system, as evidenced by increased ROS production and reductions in ACAP levels and CAT activity.

In this study, we demonstrated that chronic exposure to blue light at intensities that mimic those received by humans during the use of electronic devices (32–100 lux) induced significant alterations in the oxidative status of the retina in mice. These alterations were characterized by dysfunction of the antioxidant system, as evidenced by increased ROS production and reduced ACAP levels and CAT activity.

In our study, we observed an increase in ROS levels in the retina of mice following 2 h of blue-light exposure, both with and without photoprotection (Fig. 1). Similar results have been reported in studies using murine models [35, 37, 44, 45, 48, 66]. In these studies, increased ROS levels were observed following blue-light exposure. However, Xie et al. [35] demonstrated increased ROS levels in albino mice exposed to blue light at an intensity of 10,000 lux. Similarly, Han et al. [37] observed a marked increase in ROS levels in albino murine models exposed to 1,500 lux of blue light and in rat precursor R28 cells exposed to 1,000 lux. Likewise, Zhu et al. [44] identified increased ROS levels in albino rats with their eyelids open. The study by Zhou et al. [45] also reported increased ROS levels in albino rats exposed to blue light for 3 h daily over 45 consecutive days. Kuse et al. [48] reported increased ROS production in cone cells following exposure to blue light at an intensity of 450 lux. Consistent with these findings, the recent study by Samoila et al. [66] also demonstrated increased ROS production following exposure to blue light at an intensity of 6,000 lux.

Taken together, these data confirm that the cellular response observed in our investigation supports the metabolic vulnerability of retinal tissue to blue-light exposure. However, it is crucial to contextualize these findings, as the literature has predominantly employed experimental models that may not necessarily represent the majority of the global population. The use of albino mice and rats [35, 37, 44, 45, 66], combined with high light intensities ranging from 1,500 to 10,000 lux, may artificially increase ROS production. This effect may be further amplified in protocols involving eyelid opening or *in vitro* cell cultures directly exposed to irradiation, which lack the optical attenuation mechanisms present in the *in vivo* eye.

In contrast, the major differential and innovative value of our study lies in the simulation of a realistic physiological scenario. We used pigmented animals containing melanin, without resorting to invasive interventions such as pupillary dilation, eyelid retraction, or high light intensities. Notably, even under conditions representative of everyday exposure, we demonstrated that a short 2-h exposure to blue light was sufficient to significantly increase ROS levels in the retina, both with and without photoprotection (Fig. 1). These findings indicate that retinal tissue is highly sensitive to blue light even under normal lighting conditions, highlighting the silent and cumulative risk associated with the daily use of blue-light-emitting devices in modern life.

We also observed reduced ACAP levels following 2 and 12 h of blue-light exposure, both with and without photoprotection (Fig. 2). This finding indicates that blue light may reduce defenses against

peroxyl radicals, potentially altering protein levels, enzymatic activity, or non-enzymatic antioxidant components associated with ACAP. In other words, ACAP was most likely overloaded in an attempt to neutralize excess ROS. These findings are supported by Abdouh et al. [49], who demonstrated that increased ROS production suppresses enzymatic antioxidant systems by altering gene and enzyme expression rates. Chae et al. [50] reported non-enzymatic antioxidant activity of reduced GSH in ARPE-19 cells exposed to blue light, under which conditions GSH acted as a preventive antioxidant against photoinduced ROS generation. Similarly, Stanhope et al. [51] exposed flies to 8,000 lux of blue light for 8 h and reported a marked reduction in proteins involved in phototransduction and profound alterations in GSH/GSSG ratios, indicating a severely oxidized cellular environment. Seol et al. [52] observed a reduction in antioxidant defense capacity after 2 h of exposure to blue light at 6,000 lux in BALB/c mice, indicating antioxidant overload resulting from excessive ROS production.

In light of these findings, it is plausible that, during the initial stages of light absorption, the retinal antioxidant system is rapidly mobilized to counteract the immediate increase in ROS. This intensive mobilization requires the consumption of available antioxidant molecules, such as glutathione and related enzymes, leading to temporary depletion of antioxidant defenses. From this perspective, the decrease observed in ACAP represents the metabolic cost of an active and highly demanding compensatory antioxidant response, in which the cellular machinery operates at its limit to neutralize the photo-oxidative overload induced by blue light. Extending this perspective, the present study advances current understanding by demonstrating that this dynamic compensatory consumption does not depend on extreme lighting conditions, as it is triggered early even under moderate and realistic exposure parameters.

Our results also demonstrated that blue-light exposure rapidly reduced CAT activity (Fig. 3). This reduction was observed when animals were exposed to blue light for 12 h with a visual protection filter, indicating suppression of fundamental cellular antioxidant defense mechanisms.

In the literature, findings regarding CAT under light-induced stress show considerable variation. Consistent with our data, Marie et al. [53] observed reduced CAT activity in retinal pigment epithelium (RPE) cells subjected to direct and continuous irradiation for 15 h. Conversely, Ciccone et al. [67] found no changes in CAT expression in ARPE-19 cells exposed to wavelengths of 405–420 nm. In contrast, investigations using *Drosophila* models [54] reported induction of CAT activity following exposure to 8,000 lux for 3–5 h over 3 days, acting as a compensatory mechanism against retinal degeneration.

These differences may possibly be explained by light intensity, exposure duration, and, above all, the biological model employed. Unlike scenarios involving direct irradiation or severe light stress, the present study used a design based on indirect exposure, in which the animals were allowed to move freely within their cages. This approach preserves natural behavior and simulates a physiological pattern of ocular exposure that is much closer to real-life human conditions.

Nevertheless, the reduction in CAT activity observed in our model is consistent with the findings of Stanhope et al. [51], suggesting that the continuous accumulation of reactive species may induce direct

inactivation or oxidation of the CAT enzyme itself. Catalase represents one of the fastest and most energetically efficient pathways for hydrogen peroxide degradation. Therefore, its inactivation, even under photoprotection during the 12-h period, suggests that sustained ROS overload may have compromised a detoxification pathway, placing the retinal antioxidant system in a state of metabolic vulnerability.

In this study, blue-light exposure did not cause lipid damage (Fig. 4). Although blue light is known to damage retinal cell membranes [55; 5; 57; 58], Rózanowska et al. [55] demonstrated lipid peroxidation in human and bovine retinal cells exposed to blue light, emphasizing time- and dose-dependent effects on photo-oxidative stress. Similarly, Nakanishi-Ueda et al. [56] reported immediate lipid damage in retinal pigment epithelium cells exposed to blue light for 24 h, as indicated by strong immunofluorescent labeling for 4-hydroxy-2-nonenal (HNE), a marker of lipid peroxidation. Likewise, Chen et al. [57] demonstrated lipid peroxidation in *Drosophila melanogaster* exposed to 8,000 lux of blue light for 2–8 h, suggesting that high light intensities induce such damage. Reinforcing these previous findings, Yang et al. [58] revealed lipid peroxidation and retinal degeneration in pigmented C57BL/6J mice exposed to 3,250 lux for 30 min following prior pupillary dilation, confirming the phototoxicity of blue light.

In contrast, our results indicate distinct responses, probably due to the lower and more realistic light intensity used and the use of pigmented animals whose melanin content reduces the penetration and scattering of blue light within the retina. In addition, no pupillary dilation was induced, and retinal cells were not directly exposed. This approach, which mimics genuine human behavior, limits effective retinal exposure and potentially attenuates ROS production and lipid peroxidation levels. Thus, the stability of LPO and the preserved membrane integrity observed in our study likely reflect the compensatory activity of antioxidants such as GSH, GPx, SOD, and particularly GST [59;60].

Histological analysis of the retina revealed that blue light did not induce morphological changes following 2- and 12-h exposures to light, either with or without photoprotection (Fig. 5). Likewise, individual assessments of the retinal layers revealed no significant differences in thickness. Although some studies have demonstrated that blue-light-induced phototoxicity results in marked morphological changes in the retina, such as lesions, layer thinning, and vascular leakage [61;62;63], our findings differ.

The study by Geiger et al. [61] revealed significant retinal damage when mice were irradiated with blue light. The authors reported pyknosis and degeneration in the outer nuclear layer (ONL), as well as infiltration of microglia and macrophages at the lesion site, suggesting an inflammatory response, in addition to inflammation in the inner nuclear layer (INL). Furthermore, they detected vascular leakage, disruption of the blood–retinal barrier, retinal edema, and photoreceptor death. Lin et al. [62] used pigmented Brown Norway rats individually exposed to blue LED light for 3 h daily at 150 lux for 21 days and demonstrated reduced total retinal thickness and neuronal damage even under low-intensity light. Similarly, Theruveethi et al. [63] analyzed retinal histology in Wistar rats exposed to 450–500 lux for 12 h over 28 days and observed apoptosis and necrosis in the retinal pigment epithelium and photoreceptors.

Compared with these studies, our investigation differed in that we found no structural damage or pathological conditions in the retinal layers. However, the absence of histological lesions does not imply that blue light is harmless, as it alters the oxidative status of the retina, indicating that even moderate exposure may trigger relevant biochemical responses and potential long-term physiological alterations. Notably, the study by Lin et al. [62] employed methodologies similar to ours, particularly with regard to low illuminance and exposure duration; however, the light intensity used in our experiment was even lower (32–78 lux), and the animals were not individually placed in an exposure chamber. In view of these findings and the scarcity of studies that realistically reproduce daily blue-light exposure, our work stands out as a pioneering study simulating real-life conditions to which the human population is routinely exposed.

The effects of 2- and 12-h exposure to blue light at low intensities remain poorly explored. Song et al. [64] exposed ARPE-19 cells to blue LED light for 2 h and observed cell death in the retinal pigment epithelium and decreased protein expression. However, this phenomenon occurred after exposure to 2,200 lux, which is considerably higher than the level used in our study (38–78 lux for 2 h). Regarding 12-h exposure, Suzuki et al. [65] exposed C57BL/6 mice to blue light for the same duration at an intensity of 500–1,000 lux. The authors reported phospholipid oxidation, specifically in the outer plexiform layer, photoreceptors, retinal pigment epithelium, and choroid, as well as macrophage accumulation. Although these studies used similar exposure durations, their light intensities were not comparable, and their results provide inconsistent evidence regarding short- and long-term exposure (2 and 12 h). Considering the gaps and controversies in the literature concerning photo-oxidative and enzymatic responses at different exposure durations, the present study employs physiological parameters and realistic intensities that allow subtle effects of acute-chronic phototoxic stress to be isolated. Thus, this work provides a reference for future research by demonstrating that even plausible exposure levels can trigger depletion of antioxidant reserves.

This study also demonstrated that the photoprotective agent tested has the potential to mitigate the effects of blue light, showing an ability to reduce oxidative stress and positively modulate the cellular defense response. These findings suggest that, in the groups treated with the protective filter, there was clear interference with the photochemical damage cascade, stabilizing the cellular environment and preserving biomolecular integrity. Despite these promising findings, it is essential to emphasize that definitive validation of its efficacy and safety for human use, as well as a complete elucidation of its mechanisms of action, still requires further and more in-depth clinical analyses.

Finally, we highlight the limitations associated with the use of albino animals in studies investigating blue-light-induced damage. Albino animals lack melanin in their eyes, the natural pigment responsible for absorbing excess light and helping to counteract oxidative stress [46;47]. Because they lack this natural protection, they may experience substantially greater damage than would normally occur. Therefore, findings obtained from albino animals may not accurately reflect what occurs in the majority of humans. By using a pigmented animal model, our study overcomes this limitation, providing a more realistic and accurate assessment of the risks associated with blue-light exposure in everyday life.

Conclusion

Frequent and prolonged exposure to blue light, particularly that emitted by electronic devices, represents a relevant concern for visual health. Although current evidence does not yet allow definitive conclusions that everyday screen use causes permanent retinal damage, such exposure may be associated with visual discomfort, eye strain, and, under certain conditions, increased oxidative stress. Therefore, its potential effects should be evaluated considering factors such as light intensity, exposure duration, screen distance, environmental conditions, and individual characteristics.

In this context, prevention should combine appropriate screen-use habits, regular breaks, brightness control, adequate lighting, and ophthalmological follow-up. In parallel, the development of optical filters, controlled-emission systems, and other photoprotective technologies represents a promising approach, provided that their efficacy and safety are demonstrated through consistent and long-term scientific studies.

Thus, rather than establishing definitive conclusions regarding the risks associated with blue light, this study reinforces the importance of expanding research into its cumulative effects and promoting more conscious use of digital devices. The integration of scientific knowledge, preventive measures, and technological innovation may contribute to the preservation of ocular health and to reducing potential visual impacts in a society increasingly dependent on screens.

Declarations

7. Acknowledgments

Special thanks to the supporting institutions that contributed significantly to the development of this research: CAPES, the Federal University of Rio Grande (FURG), and the Institute of Biological Sciences of the Federal University of Rio Grande (Brazil).

Declaration of competing interest:

We have nothing to declare.

Data availability:

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Approval for animal experiments:

The animal study protocol was approved by the Animal Use Ethics Committee of the Federal University of Rio Grande (CEUA-FURG; approval protocol number P024/2022).

Compliance with guidelines and regulations:

We confirm that all the experiments were conducted in strict accordance with national and international guidelines applicable to animal welfare, including current Brazilian legislation (Law No. 11.794/2008, Decree No. 6.899/2009) and the recommendations of the National Council for the Control of Animal Experimentation (CONCEA). All possible measures were taken to minimize pain, stress, and discomfort for the animals used in the research.

Compliance with ARRIVE guidelines:

We declare that the authors fully adhered to the ARRIVE guidelines (Animal Research: Reporting of In Vivo Experiments) in the preparation and reporting of the methods, ensuring rigor, transparency, and reproducibility in the experimental description.

Funding

This study received no specific funding. The author was supported by a master's scholarship from CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brazil; Finance Code 001), which did not include funding for research or publication costs.

Author Contributions

Magayver Melo de Oliveira: Responsibility for all aspects of the work: participation, writing the initial draft, and active participation in the design of the technical aspects of the work.

Suzana Lemke Lanius: Active participation in the design of the technical aspects of the work.

Livia Silveira Munhoz: Active participation in the design of the technical aspects of the work.

Marcelo Alves Vargas: Active participation in the design of the work, critical review of the intellectual content, approval of the final version of the text to be published, and project coordination.

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Figures

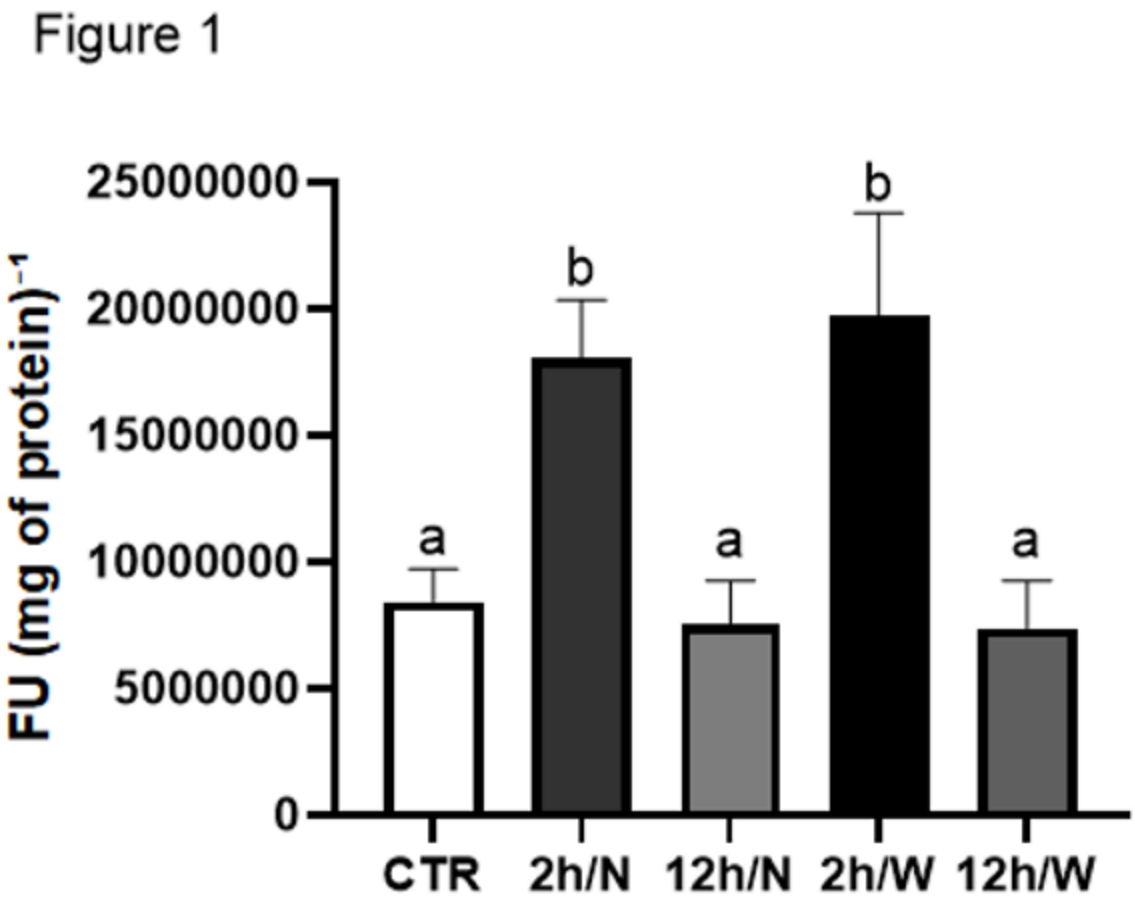


Figure 1

ROS concentration in the retina. Group 1; CTR: Group 2; 2 h/N: Group 3; 12 h/N: Group 4; 2h/W: Group 5;12 h/W. Different letters represent a significant difference at $p < 0.05$ (one-way ANOVA and Newman–Keuls comparison tests).

Figure 2

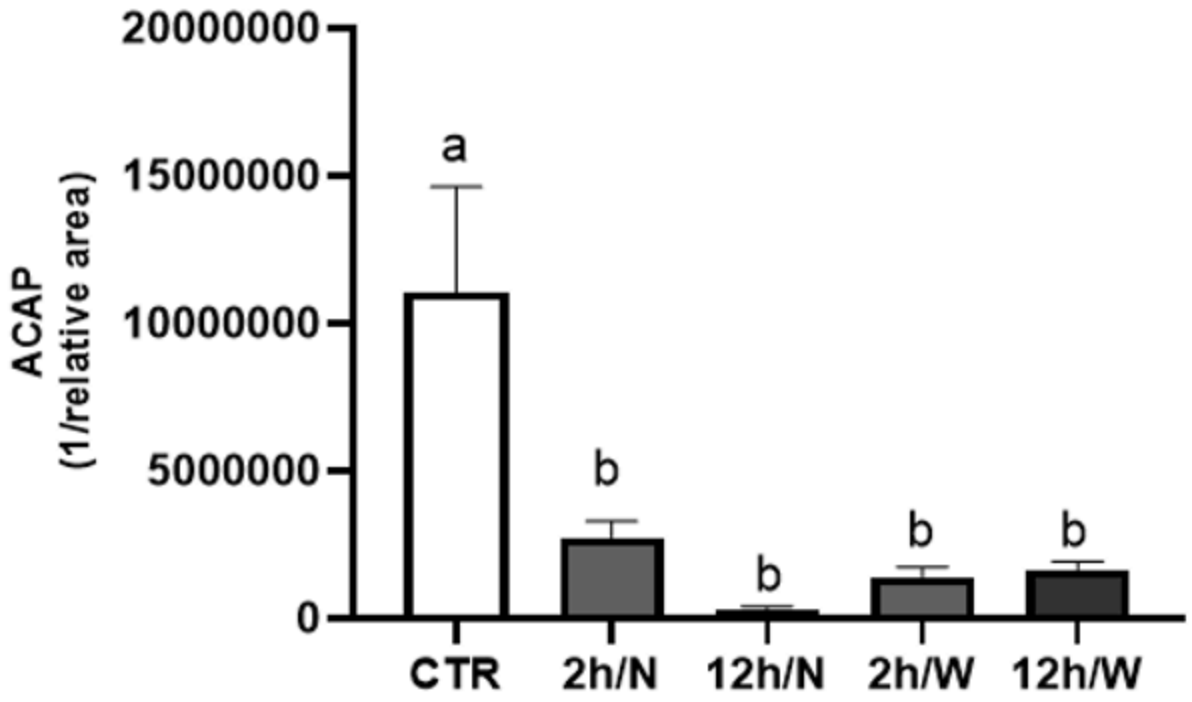


Figure 2

ACAP concentration in the retina. Group 1; CTR: Group 2; 2 h/N: Group 3; 12 h/N: Group 4; 2h/W: Group 5;12 h/W. Different letters represent a significant difference at $p < 0.05$ (one-way ANOVA and Newman–Keuls comparison tests).

Figure 3

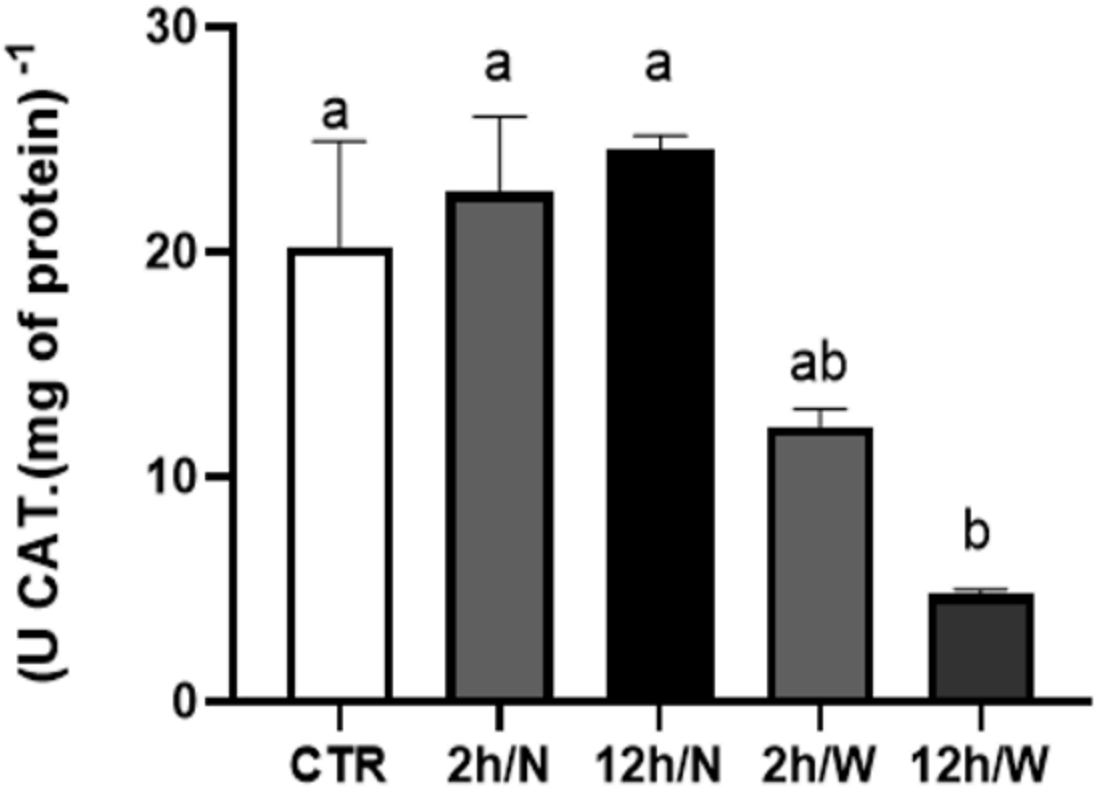


Figure 3

CAT concentration in the retina. Group 1; CTR: Group 2; 2 h/N: Group 3; 12 h/N: Group 4; 2h/W: Group 5;12 h/W. Different letters represent a significant difference at $p < 0.05$ (one-way ANOVA and Newman–Keuls comparison tests).

Figure 4

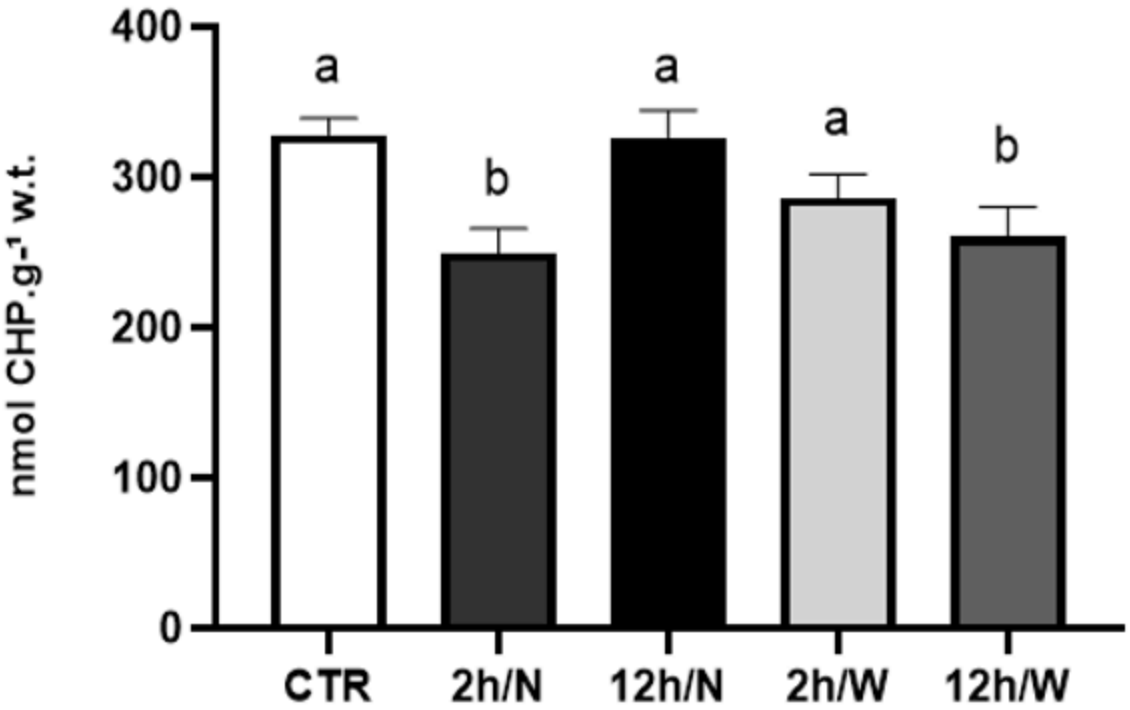


Figure 4

Concentration of LPO in the retina. Group 1; CTR: Group 2; 2 h/N: Group 3; 12 h/N: Group 4; 2h/W: Group 5;12 h/W. Group 5. Different letters represent a significant difference at $p < 0.05$ (one-way ANOVA and Newman–Keuls comparison tests).

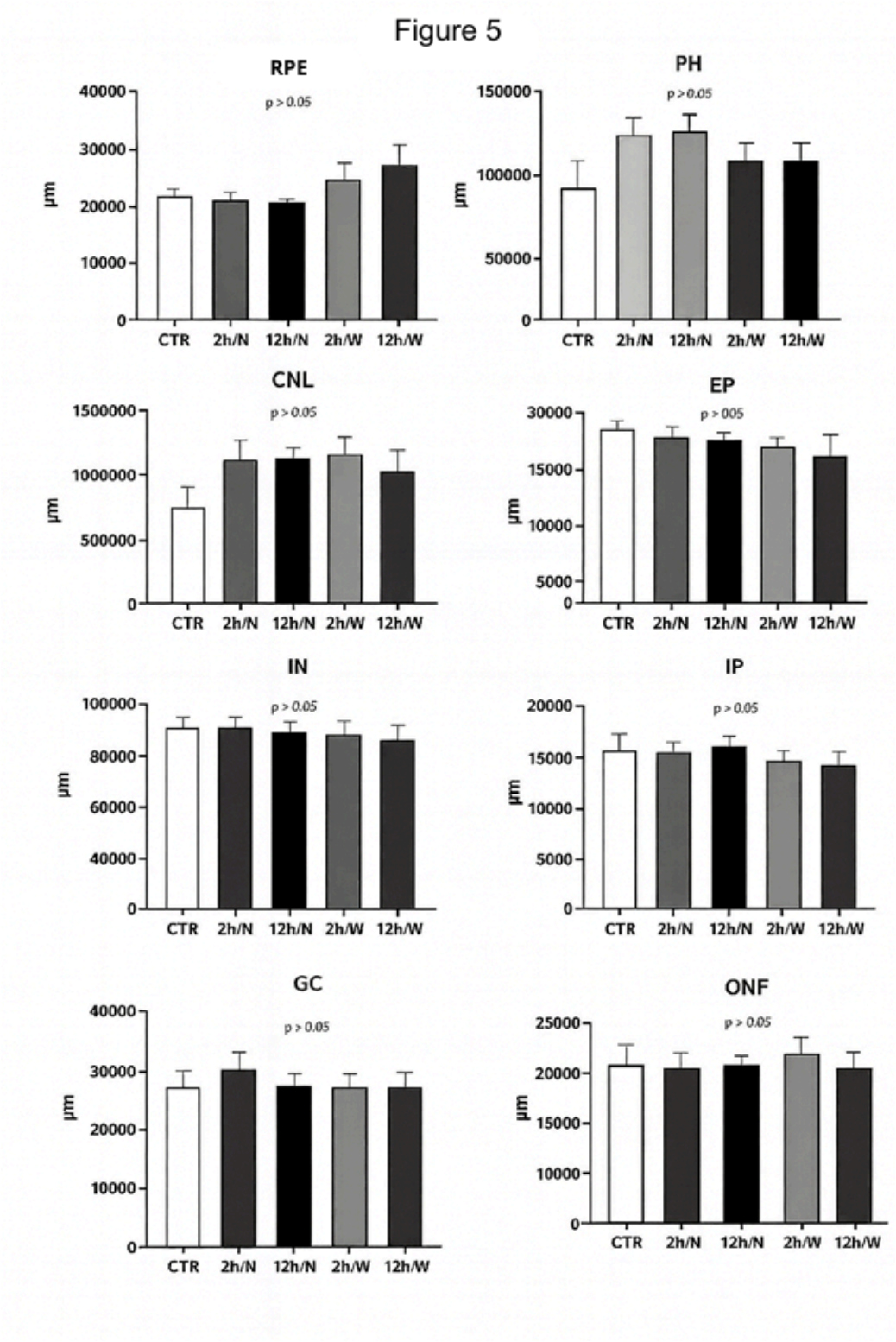


Figure 5

Histological analysis of the retina. Group 1; CTR: Group 2; 2 h/N: Group 3; 12 h/N: Group 4; 2h/W: Group 5;12 h/W. No significant differences were observed ($p > 0.05$; one-way ANOVA and Newman–Keuls comparison tests). Respective layers: retinal pigment epithelium (RPE); photoreceptors (PH); outer nuclear layer (CNL); outer plexiform layer (EP); inner nuclear layer (IN); inner plexiform layer (IP); ganglion cell layer (GC); and optic nerve fibers (ONF).

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