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ISNI: 0000 0004 8495 2390

Dolna 17, Warsaw,
Poland 00-773
+48 226 0 227 03
editorial_office@rsglobal.pl

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# BLUE LIGHT EXPOSURE AND RETINAL HEALTH: MYTHS, EVIDENCE, AND THE ROLE OF BLUE LIGHT-BLOCKING INTERVENTIONS

***Weronika Ossowska*** *(Corresponding Author, Email: ossowska.w@gmail.com)*
*PCK Maritime Hospital, Gdynia, Poland*
*ORCID ID: 0009-0002-4205-9572*

***Karolina Wojdat-Krupa***
*PCK Maritime Hospital, Gdynia, Poland*
*ORCID ID: 0009-0003-0942-8273*

***Wiktoria Ösztreicher***
*University Clinical Hospital No. 1, Szczecin, Poland*
*ORCID ID: 0009-0000-6090-8369*

***Paulina Lewaśkiewicz***
*University of Pavol Jozef Safarik, Košice, Slovakia*
*ORCID ID: 0009-0008-2361-4917*

***Karol Sikora***
*University of Pavol Jozef Safarik, Košice, Slovakia*
*ORCID ID: 0009-0009-5610-3547*

***Filip Lachowski***
*PCK Maritime Hospital, Gdynia, Poland*
*ORCID ID: 0000-0001-5451-4996*

**ABSTRACT**

**Aims:** With the widespread use of digital devices and LED-based lighting, exposure to artificial blue light has significantly increased in recent years. This has raised concerns about potential retinal damage, disruption of circadian rhythms, and digital eye strain. At the same time, the market for blue light-blocking interventions, such as specialty eyewear and screen filters, has expanded rapidly. The aims of this review is to assess current scientific evidence on the biological effects of blue light on retinal health, evaluate the effectiveness of blue light-blocking strategies, and clarify common misconceptions.
**Methods:** A narrative literature review was conducted using PubMed, Scopus, and Web of Science databases. Peer-reviewed articles published between 2010 and 2025 were included. The review focused on studies examining the retinal effects of blue light exposure, the pathophysiological mechanisms involved (including oxidative stress and phototoxicity), and clinical trials evaluating the use of blue light filters and digital ergonomics in reducing visual fatigue and sleep disruption.
**Results:** Although experimental models suggest that high-intensity blue light may contribute to retinal oxidative stress, current clinical evidence does not support a direct link between typical screen exposure and long-term retinal damage. Blue light-blocking glasses show limited efficacy in reducing eye strain or improving sleep in the general population. Misconceptions about blue light toxicity persist, often driven by commercial claims rather than scientific validation.
**Conclusions:** Blue light from screens poses minimal risk to retinal integrity under normal use conditions. Preventive strategies such as screen breaks, proper lighting, and digital ergonomics appear more effective than blue-blocking products. Health education efforts should focus on evidence-based practices rather than marketing-driven solutions.

**KEYWORDS**

Blue Light, Retina, Oxidative Stress, Sleep, Protective Devices, Screen Exposure

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## Introduction

Over the past two decades, the widespread adoption of LED-based lighting and the ubiquity of digital screens have dramatically increased human exposure to artificial blue light. Blue light, with wavelengths between 400 and 490 nanometers, is the highest-energy portion of the visible spectrum and is known to penetrate deep into the eye, reaching the retina [1,2]. This has raised public and scientific concern about the potential cumulative effects of prolonged exposure on ocular structures, particularly the retinal pigment epithelium (RPE) and photoreceptor cells.

Blue light has been implicated in inducing oxidative stress, mitochondrial dysfunction, and photochemical damage in retinal cells under certain experimental conditions [3–5]. In vitro and in vivo models have demonstrated that short-wavelength visible light can initiate reactive oxygen species (ROS) formation, leading to lipid peroxidation and apoptotic cell death [6]. However, the relevance of these findings to typical human screen usage remains controversial. Some researchers argue that the intensities used in laboratory studies far exceed those encountered in real-world scenarios [7]. The impact of blue light extends beyond the retina. Exposure during evening hours has been shown to suppress melatonin production and disrupt circadian rhythms, contributing to sleep disturbances and fatigue [8,9]. These physiological effects have led to the commercialization of various blue light-blocking interventions, including specialized lenses, software filters, and LED lighting modifications. Despite their popularity, the actual efficacy of such interventions is still under debate, with several randomized trials showing minimal or inconsistent benefits for visual comfort or sleep quality [10].

Given the increasing reliance on digital technologies across all age groups and the expanding market of blue light-blocking products, it is critical to distinguish between scientifically grounded concerns and commercially driven myths. This review aims to clarify the current evidence on the biological and clinical impact of blue light exposure on retinal health, assess the effectiveness of blue light-filtering strategies, and critically evaluate the prevailing narratives surrounding “blue light toxicity”.

## Methodology

This review was conducted as a narrative literature analysis focusing on the biological effects of blue light exposure and the efficacy of blue light-blocking interventions. Relevant studies were identified through searches in PubMed, Scopus, and Web of Science databases, covering publications from 2010 to 2025. The search terms included combinations of “blue light, retina”, “oxidative stress”, “sleep”, “protective devices”, “screen exposure”. Only peer-reviewed articles published in English were considered. Eligible papers included experimental, clinical, and review studies addressing retinal effects, physiological responses, or the impact of blue light on vision and sleep. Studies lacking original data, non-peer-reviewed sources, and publications unrelated to ocular health were excluded. Data were synthesized qualitatively and grouped into key thematic categories: retinal phototoxicity, circadian disruption, blue light-blocking strategies, and pediatric implications.

## Results

### Retinal Phototoxicity and Oxidative Stress Induced by Blue Light

Exposure to blue light has been shown to induce retinal damage through photochemical mechanisms that primarily involve oxidative stress and mitochondrial dysfunction. The retina, due to its high metabolic activity and oxygen consumption, is particularly vulnerable to reactive oxygen species (ROS) generated during light exposure. These effects are exacerbated in the presence of endogenous photosensitizers such as lipofuscin and its component A2E (N-retinylidene-N-retinylethanolamine), which accumulate in retinal pigment epithelial (RPE) cells with age and disease [11]. In vitro studies have demonstrated that blue light (typically 415–455 nm) exposure induces significant increases in ROS production, lipid peroxidation, DNA fragmentation, and apoptosis in cultured retinal cells, particularly in ARPE-19 cell lines loaded with A2E [12,13]. Mitochondria, as the primary energy-producing organelles, are both major sources and targets of ROS

during blue light-induced damage. Mitochondrial swelling, membrane depolarization, and cytochrome c release have all been observed following light exposure, leading to caspase activation and programmed cell death [14].

Phototoxicity is highly dependent on both the intensity and duration of exposure. Experiments using light-emitting diodes (LEDs) of varying blue wavelengths have shown dose-dependent damage to photoreceptors and RPE cells. Prolonged or repeated exposures—particularly under high luminance conditions—can accelerate oxidative damage beyond the endogenous antioxidant defense capabilities of the retina [15]. Animal models have corroborated these findings. Mice and rat studies have shown retinal thinning, photoreceptor disorganization, and decreased expression of retinal function markers following chronic blue light exposure. These changes are especially pronounced in genetically susceptible models or in animals with pre-accumulated A2E or lipofuscin [16]. Notably, light-induced degeneration mimics certain features of age-related macular degeneration (AMD), suggesting that blue light might exacerbate or accelerate pre-existing degenerative processes [17]. While these models establish a mechanistic basis for concern, it is critical to note that many of the light intensities used in laboratory studies far exceed those encountered in daily human screen use. The translation of these findings to clinical risk remains controversial and context-dependent.

**Experimental and Animal Studies: Dose and Duration Effects**

A substantial body of experimental evidence has evaluated the effects of blue light exposure using animal models and controlled in vivo experiments. These studies offer crucial insights into how dose (intensity), duration, and wavelength of blue light determine its potential to induce retinal injury. In rodent models, repeated exposure to high-intensity blue light has been shown to result in histological changes such as thinning of the outer nuclear layer (ONL), photoreceptor disorganization, and increased apoptosis in retinal layers [18]. The severity of damage is strongly influenced by cumulative dose: both the irradiance level (measured in lux or $W/m^2$) and exposure time significantly impact cellular viability. In most studies, phototoxicity becomes evident at intensities exceeding 5000 lux over several hours, well above ambient indoor lighting or screen levels [19]. Wavelength specificity is another important variable. Light within the 400–460 nm range tends to have the highest biological impact due to greater photon energy and its absorption by chromophores such as A2E and mitochondrial cytochromes [20]. In vivo imaging and electrophysiological recordings in mice and rats have demonstrated reduced retinal responses (ERG amplitude suppression) and delayed functional recovery following exposure to short-wavelength blue light compared to longer wavelengths [21]. Importantly, some animal studies have attempted to mimic chronic, low-level exposure resembling real-life digital device use. In these models, blue light exposure over weeks or months has yielded only mild or reversible retinal effects, suggesting that acute high-intensity illumination, not long-term screen use, poses the main risk [22]. Nevertheless, specific models—such as albino rodents or genetically modified mice with impaired antioxidant defenses—have shown greater vulnerability, highlighting the role of genetic and physiological predispositions [23]. These findings underscore the importance of exposure context when evaluating blue light hazards. While experimental systems can isolate and intensify variables for mechanistic insight, their relevance to typical human screen behavior must be interpreted with caution.

**Human Observational and Clinical Studies**

Despite compelling in vitro and animal evidence, the clinical significance of blue light exposure from digital devices in humans remains a subject of debate. Numerous observational and interventional studies have assessed the potential impact of screen-emitted blue light on retinal health, digital eye strain, and visual performance. To date, no large-scale epidemiological studies have demonstrated a direct link between screen use and permanent retinal damage or the development of conditions such as age-related macular degeneration (AMD). Population-based studies, including those that follow individuals over decades, attribute AMD risk primarily to aging, genetic predisposition, smoking, and UV exposure—not to screen-related light [24,25]. Several clinical studies have explored symptoms associated with digital eye strain (also known as computer vision syndrome), such as eye fatigue, dryness, and blurred vision. While these symptoms are commonly reported by frequent screen users, they are more closely related to reduced blinking, poor lighting conditions, and uncorrected refractive errors than to blue light per se [26]. Controlled trials evaluating blue light-filtering glasses have shown minimal or inconsistent effects in reducing self-reported eye strain, suggesting that the perceived benefits may be due to placebo or other ergonomic improvements [27].

Blue light exposure has also been investigated in relation to visual performance. Studies examining contrast sensitivity, visual acuity, and macular function after screen use have generally failed to find any

significant or lasting changes, even in subjects with prolonged daily exposure [28]. In healthy adults, blue light levels emitted by smartphones, tablets, and computer screens fall well below phototoxic thresholds defined by international safety guidelines. Importantly, existing clinical trials are often limited by small sample sizes, short follow-up durations, and subjective outcome measures. There is a lack of long-term, high-quality human studies that replicate the intensity and conditions of experimental models. As such, while caution is reasonable, current evidence does not support the idea that everyday screen exposure leads to cumulative retinal damage in healthy individuals [29].

**Circadian Disruption and Sleep Effects**

Beyond potential retinal damage, one of the most studied physiological consequences of blue light exposure is its impact on the circadian system and sleep regulation. Short-wavelength light, particularly around 460–480 nm, plays a key role in synchronizing the human biological clock through non-image-forming pathways in the retina. Intrinsically photosensitive retinal ganglion cells (ipRGCs), which contain the photopigment melanopsin, are especially sensitive to blue light and project directly to the suprachiasmatic nucleus (SCN)—the master regulator of circadian rhythms [30]. Evening exposure to blue light has been shown to suppress melatonin secretion, delay sleep onset, and reduce sleep duration and quality [31]. These effects are most pronounced when exposure occurs within two hours before bedtime and under bright lighting or close screen proximity. Experimental studies in humans confirm that blue-enriched light in the evening phase can alter physiological markers such as melatonin levels, core body temperature, and sleep architecture. Adolescents and young adults appear particularly vulnerable due to delayed circadian phase preference and increased screen use [32]. These findings have spurred widespread concern over "circadian disruption" caused by excessive evening screen time. However, the extent of these effects in real-world conditions remains variable. Randomized controlled trials testing blue light-blocking interventions—such as amber lenses or software filters (e.g., f.lux, Night Shift)—have produced mixed results. Some studies report modest improvements in sleep onset latency and melatonin levels, while others find no significant difference compared to controls [33,34]. The degree of disruption appears to depend on multiple factors including individual chronotype, light intensity, spectral composition, and behavioral habits (e.g., screen distance, room lighting). Importantly, even ordinary indoor lighting may contain enough blue wavelengths to impact circadian biology, making comprehensive light hygiene (including limiting overhead LED lights) equally important [35].

**Efficacy of Blue Light-Blocking Interventions**

In response to growing concerns about blue light exposure, a wide array of commercial interventions have been developed, including blue light-filtering glasses, software-based screen filters, and LED lighting modifications. These interventions aim to reduce visual fatigue, improve sleep quality, and mitigate potential retinal damage. Blue light-blocking glasses, often marketed with amber or yellow lenses, filter out a portion of short-wavelength light before it reaches the eye. Randomized controlled trials (RCTs) testing these glasses in the general population have shown mixed outcomes. Some studies report minor improvements in subjective eye comfort or sleep onset latency, while others demonstrate no statistically significant benefit compared to placebo lenses [36]. Notably, many trials are underpowered, with short durations and highly variable endpoints. Software-based solutions, such as Apple's Night Shift or the f.lux application, modify screen emission spectra by reducing blue light components in the evening hours. Though widely adopted, these features have not consistently demonstrated improvements in sleep or cognitive performance in controlled studies [37]. The perceptual change in screen tint may influence user behavior (e.g., perceived fatigue), but measurable physiological outcomes remain limited. Interventions in occupational settings, such as blue light-filtering intraocular lenses (IOLs) or modified LED lighting environments, have also been explored. These studies typically focus on older adults or night-shift workers. Some evidence suggests that blue light attenuation may reduce glare and improve contrast sensitivity in aging eyes, but the clinical relevance remains modest [38]. Furthermore, digital eye strain is a multifactorial condition. Factors such as screen glare, text size, contrast, ambient lighting, blink rate, and posture often have greater influence than spectral properties alone. Meta-analyses suggest that ergonomic interventions—like scheduled breaks (20-20-20 rule), artificial tear supplementation, and environmental lighting control—may be more effective than blue-blocking filters alone [39,40]. Overall, while blue light-blocking interventions are generally safe and may offer subjective benefits for some individuals, the scientific evidence does not support their routine use for the prevention of retinal disease or significant sleep improvement.

**Blue Light Exposure in Children and Adolescents**

The increasing integration of digital technology into the lives of children and adolescents has raised concerns regarding the potential long-term effects of blue light exposure during critical stages of ocular and neurodevelopment. This population is particularly vulnerable due to a combination of behavioral, anatomical, and physiological factors. Anatomically, children's eyes have larger pupils and more transparent crystalline lenses, allowing more short-wavelength (blue) light to reach the retina compared to adults [41]. Moreover, their intrinsically photosensitive retinal ganglion cells (ipRGCs) may be more reactive, influencing sleep-wake cycles and melatonin suppression with relatively lower light exposure [42]. Behavioral patterns such as extended screen time, especially in the evening, further amplify the potential for circadian disruption [43]. Emerging research suggests that excessive evening screen use among children is associated with delayed sleep onset, reduced sleep duration, and poorer academic performance [44,45]. Adolescents are also more prone to phase delays in their circadian rhythms, making them biologically predisposed to staying up late — a tendency exacerbated by blue light exposure [46]. Despite growing parental interest in blue-light filtering eyewear and software solutions, studies on their efficacy in children remain limited. A randomized trial involving teenage boys found that blue-blocking glasses improved melatonin levels and sleep quality when worn in the evening, though effects were modest and context-dependent [47]. Additionally, some pediatricians caution that overemphasis on blue light may obscure more important behavioral contributors to poor sleep and digital eye strain, such as lack of outdoor activity, excessive near work, and insufficient screen breaks [48]. There is also increasing concern over the lack of formal guidelines regarding digital screen exposure and blue light mitigation for pediatric populations. Most existing recommendations are extrapolated from adult data, despite the physiological and behavioral differences. Recent expert reviews have called for age-specific exposure limits, especially in educational settings that increasingly rely on tablets and e-learning tools [49,50]. In conclusion, while blue light exposure in children and adolescents is not yet definitively linked to retinal pathology, its effects on sleep architecture, circadian timing, and visual comfort warrant more targeted investigation. Preventive strategies should prioritize screen-time management, digital hygiene education, and incorporation of natural light exposure throughout the day.

**Efficacy of Blue Light-Blocking Software and Applications**

As awareness of blue light's potential effects on sleep and visual comfort has grown, a number of software-based solutions have been developed to mitigate exposure, particularly from digital screens. These include built-in features such as Apple Night Shift, Android Night Mode, Windows Night Light, and third-party applications like f.lux, all of which aim to reduce the emission of short-wavelength blue light during evening hours. These systems function by shifting the color temperature of the display toward warmer hues, thus reducing melanopic lux and potentially limiting melatonin suppression in the hours before sleep [51]. However, the actual clinical efficacy of such software in improving sleep or preventing visual symptoms remains debated. Experimental studies using these filters show small but statistically significant improvements in melatonin levels and sleep onset latency when compared to standard screen settings [52]. For instance, a controlled study comparing f.lux-enabled laptops with unfiltered screens found that evening use of the filtered display resulted in less melatonin suppression and marginally improved subjective sleep quality [53]. Nevertheless, these results vary widely based on screen size, brightness settings, individual chronotype, and ambient lighting. Moreover, not all blue light filtering algorithms are equivalent. Some mobile apps adjust display temperature only slightly, without substantially affecting melanopic light exposure [54]. There is also limited evidence regarding visual comfort or reduction of digital eye strain. While warmer color tones may subjectively feel less harsh, controlled trials have failed to demonstrate consistent improvements in visual fatigue or blink rate with software filters alone [55]. Despite their popularity, experts caution against viewing these tools as standalone protective strategies. They are best used as part of a broader behavioral approach that includes screen breaks, proper room lighting, and adherence to sleep hygiene practices [56].

**Discussion**

The growing concern over blue light exposure reflects a broader tension between modern digital lifestyles and long-term ocular health. While mechanistic and preclinical studies offer compelling insights into potential phototoxic effects of short-wavelength visible light, especially in the context of oxidative stress and mitochondrial dysfunction, the clinical translation of these risks remains limited. As shown in experimental models, blue light can indeed cause structural and biochemical changes in retinal cells, particularly when exposure is intense, prolonged, or coupled with sensitizers such as A2E [11,12,14]. However, these models

often involve light intensities far exceeding those emitted by digital screens. In contrast, human observational and clinical studies fail to establish a consistent or causal relationship between screen use and retinal degeneration [24,25,56]. The widespread use of digital devices has coincided with a rise in self-reported symptoms like eye fatigue and sleep disturbances. While it may be tempting to attribute these effects solely to blue light, the underlying causes are likely multifactorial. Reduced blink rate, improper screen ergonomics, uncorrected refractive errors, and prolonged near work all contribute significantly to digital eye strain [26,40,58]. Interventions targeting these broader factors may offer more substantial benefits than blue light-specific solutions alone. Regarding circadian health, evening blue light exposure does have measurable physiological effects, especially through melanopsin-containing ipRGCs that influence melatonin secretion and sleep regulation [30,31,57]. Yet, the magnitude of these effects in everyday environments varies widely based on screen brightness, distance, exposure timing, and individual chronotype. Blanket recommendations for blue light blocking may oversimplify a complex interplay of behavioral and biological factors. Despite their popularity, blue light-filtering glasses and software have shown inconsistent outcomes in clinical trials. Systematic reviews and meta-analyses suggest that these interventions may yield small subjective improvements, but fail to produce robust changes in objective sleep quality or visual performance [36,37]. Additionally, many commercial products lack standardized filtering criteria, leading to wide variability in efficacy across brands. It is also important to distinguish between real biological risk and marketing-driven fear. The term “blue light toxicity” is frequently used in advertising without adequate scientific context. Regulatory and health organizations, including the American Academy of Ophthalmology, have stated that there is currently no evidence that digital blue light causes eye disease or permanent damage. Emphasis should instead be placed on evidence-based practices: taking regular screen breaks, maintaining proper viewing distances, and optimizing ambient lighting. Emerging research suggests that individual variability plays a major role in sensitivity to light exposure. Genetic polymorphisms, ocular pigmentation, age-related changes, and prior exposure history may all influence retinal resilience or circadian response to light stimuli [47,48]. Future studies should stratify participants accordingly and include long-term outcomes, particularly in vulnerable populations such as children, shift workers, and individuals with pre-existing retinal conditions. In conclusion, while blue light poses a theoretical hazard under extreme or artificial conditions, current evidence does not support significant health risks from everyday digital screen use. Misconceptions about blue light should be addressed through public education grounded in science rather than commercial hype. Preventive strategies should focus on holistic digital ergonomics, circadian-friendly lighting habits, and healthy screen behaviors.

## Conclusions

Blue light exposure from digital devices has become an unavoidable aspect of modern life. While laboratory studies provide mechanistic evidence of blue light-induced oxidative stress and phototoxicity in retinal cells, these findings do not translate directly to real-world screen usage. The intensity and duration of exposure from everyday devices are well below established phototoxic thresholds, and current clinical evidence does not support a link between screen use and retinal damage in healthy individuals. Nevertheless, blue light can influence circadian physiology and sleep quality, particularly when exposure occurs in the evening. In this context, interventions such as limiting screen use before bedtime and optimizing environmental lighting may offer practical benefits. However, blue light-blocking products—while widely marketed—have demonstrated limited efficacy in improving visual comfort or sleep outcomes in the general population. Digital eye strain, often mistakenly attributed to blue light, is more effectively addressed through behavioral and ergonomic interventions, such as regular breaks, screen distance optimization, and blink training. Overall, public concern regarding blue light toxicity appears to outpace scientific evidence. Education and clinical recommendations should emphasize balanced, evidence-based strategies for healthy digital habits rather than rely on commercially promoted filters or lenses. Future research should focus on long-term studies in vulnerable populations and on refining our understanding of individual variability in light sensitivity.

## Conflict of Interest Declaration

The author declares that there are no conflicts of interest regarding the publication of this work.

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