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The Impact of Blue Light Exposure on Public Health and Protective Strategies

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Abstract

This review offers an in-depth analysis of the implications of blue light exposure on public health, encompassing ocular diseases, such as ocular surface inflammation and retinal damage, alongside its potential impact on circadian rhythms, mood, and skin health. Amidst technological advancements and lifestyle changes, particularly during the COVID-19 pandemic, there has been a significant surge in indoor activities and the utilization of visual display terminals, thus highlighting the mounting concern over blue light exposure. The current study delineates the fundamental concepts, sources, and pathways of blue light exposure, and delves into the mechanisms underlying its health effects. Furthermore, it proposes a comprehensive array of protective strategies, encompassing adjustments in personal habits, dietary interventions, and medical safeguards. Future research endeavors should further elucidate the mechanisms of action of blue light to facilitate the development of more effective protective measures.

Keywords: blue light exposure, public health, ocular surface inflammation, retinal damage, circadian rhythms, protective strategies

1. Introduction

The human eye exhibits a high degree of sensitivity to the visible spectrum of light, spanning from violet (380 nm) to red (780 nm), encompassing a sequential range of colors (Norton B, Balick M, Hobday R, Fournier C, Scartezzini JL, Solt J, et al., 2017). Within this spectrum, blue light, with wavelengths between 380 and 500 nm, possesses the highest energy.

In modern life, exposure to artificial sources of blue light, primarily from indoor fluorescent and LED lighting, is pervasive. The widespread adoption of LED backlight technology in digital devices has significantly increased screen time, with a study in the United States revealing that approximately 60% of the population spends over five hours daily in front of electronic screens (The Vision Council, 2016). This trend not only alters lifestyles but also heightens reliance on artificial light sources, potentially posing adverse effects on ocular health (Ouyang X, Yang J, Hong Z, Wu Y, Xie Y & Wang G, 2020).

The cumulative exposure to various types of light, over time, influences the structure, function, and appearance of the human eye. The prevalent use of LED lighting and the increasing duration of screen use exacerbate the risk of age-related ocular diseases among the elderly. Additionally, adolescents growing up in environments with intense blue light exposure are at a higher risk of developing ocular diseases in the future (Cougnard-Gregoire A, Merle BMJ, Aslam T, Seddon JM, Aknin I, Klaver CCW, Garhöfer G, Layana AG, Minnella AM, Silva R & Delcourt C., 2023).

Hence, the issue of blue light exposure has emerged as a crucial health concern. Modern medicine increasingly recognizes the need to comprehensively understand the long-term implications of blue light on ocular and general health. Therefore, researching and widely promoting strategies to mitigate blue light exposure and safeguard ocular health have become increasingly urgent and vital.

2. Sources and Pathways of Blue Light Exposure

2.1 Natural Light Sources

Blue light originates from a diverse array of sources, including natural phenomena such as the sun, moon, and flames, alongside artificial sources. The sun, being the most potent natural light source, attains a luminance of approximately 1.6×10^9 cd/m^2 at noon, whereas a clear sky radiates around 5000 cd/m^2. In comparison, the luminance of common television displays and computer screens is substantially lower, at approximately 300 cd/m^2 and 150-250 cd/m^2, respectively.

According to ASTM G173-03 and the D65 standard, the proportion of blue light in sunlight ranges from 24-30%. Its spectral intensity varies diurnally, peaking at noon and waning at sunrise and sunset. The human body has evolved to synchronize its circadian rhythm with these ambient light variations. Additionally, the intensity of solar blue light is influenced by multiple factors, including geographic latitude, altitude, season, and meteorological conditions, which collectively determine the characteristics of blue light in diverse regions and timeframes (Leid J., 2016).

2.2 Artificial Light Sources

Blue light also stems from artificial sources, with its spectral distribution varying significantly based on the type of light source, notably LED technology. LEDs are widely adopted in modern applications due to their energy efficiency, performance, and durability, particularly in lighting fixtures, computers, and mobile devices (O'Hagan J. B., Khazova M. & Price L. L., 2016). Nevertheless, the emission of short-wavelength blue light from LEDs has sparked concerns regarding photobiological safety, which focuses on assessing the potential hazards of light source radiation on the human body, particularly the eyes. Prolonged exposure to blue light from LEDs may induce retinal damage, and this cumulative exposure spans both indoor and outdoor environments, as well as light emitted from electronic displays.

Given the high-energy nature of blue light and the widespread utilization of LEDs in digital devices, the blue component of LED emission spectra has garnered significant attention from organizations like the International Commission on Non-Ionizing Radiation Protection (Touitou Y. & Point S., 2020). Although current research indicates that the blue light emitted by digital devices such as smartphones and tablets remains well within safety thresholds, even under prolonged exposure, the question of whether long-term exposure can lead to cumulative degenerative effects remains a topic requiring further exploration (Wong NA & Bahmani H., 2022).

3. The Impact of Blue Light Exposure on Ocular Health

3.1 Ocular Surface

The entire solar spectrum, including blue light, and light from artificial sources, is perceived by the eyes and relayed to the brain via the retina, conveying environmental cues for both visual and non-visual functions. In this transmission, radiation from sunlight or artificial sources is initially absorbed or transmitted by ocular tissues like the cornea and lens before reaching the retina (Behar-Cohen F, Martinsons C, Viénot F, Zissis G, Barlier-Salsi A, Cesarini JP, et al., 2011).

Prolonged exposure to short-wavelength blue light, specifically high-energy blue-violet and some long-wave blue light, can harm the ocular surface via various biological mechanisms. These mechanisms primarily encompass oxidative stress damage, ocular surface inflammation, and cellular apoptosis. These changes not only elevate the toxicity of blue light for Dry Eye Disease (DED) patients but also directly contribute to the development and progression of DED, a prevalent ocular condition that affects millions worldwide (Stapleton F, Alves M, Bunya VY et al., 2017).

To explore the effects of blue light on ocular surface epithelial cells, Marek et al. conducted irradiation experiments using human conjunctival and corneal epithelial cells, simulating the DED pathological environment. Their results showed that these cells are highly sensitive to blue-violet and long-wave blue light. Specifically, exposure to 420 nm blue light led to decreased cell viability, abnormal morphology, and ROS overproduction. Moreover, hyperosmotic stress exacerbated the phototoxic effects, promoting inflammation, altering mitochondrial membrane potential, and activating the glutathione-based antioxidant system (Marek V, Mélik-Parsadaniantz S, Villette T, Montoya F, Baudouin C, Brignole-Baudouin F, et al., 2018).

These findings provide insights into the impact of blue light on ocular surface cells and a scientific basis for protective strategies. Further research on the long-term effects and effective protective measures against blue light exposure on ocular health is warranted.

3.2 Macular Degeneration

Age-related Macular Degeneration (AMD), a chronic visual impairment, is linked to central retina degeneration (Amini MA, Karbasi A, Vahabirad M, Khanaghaei M & Alizamir A., 2023). Demographic, genetic, and environmental studies suggest AMD's association with environmental risks. The connection between AMD and blue light exposure is increasingly studied. Blue light exposure elevates Reactive Oxygen Species (ROS) in the retina, causing abnormal oxygen metabolism, oxidative stress, and redox imbalance. Lipofuscin accumulation in retinal pigment epithelial cells exacerbates oxidative damage, promoting AMD development (Marie M., Gondouin P., Pagan D., et al., 2019). However, the precise role of blue light in AMD pathogenesis remains unclear.

The widespread use of Visual Display Terminals (VDTs) poses visual problems, including blurred vision and eye fatigue (Marie M., Gondouin P., Pagan D., et al., 2019). Retinal light damage ranges from phototoxic injuries under long-term low-level light exposure to acute injuries under short-term high-intensity light exposure. While previous studies focused on acute injuries by high-intensity white and blue light, the chronic damage caused by low-intensity blue light in daily life merits attention (Stapleton F, Alves M, Bunya VY et al., 2017).

Through observational clinical studies, Li et al. discovered that prolonged low-level exposure to blue light can significantly impair macular function, especially among individuals with extensive and frequent VDT usage. Animal experiments further revealed that chronic retinal light damage involves multiple retinal layers, accumulates over time, and can result in photoreceptor death, a severe consequence of blue light-induced retinal damage (Li H., Zhang M., Wang D., Dong G., Chen Z., Li S., Sun X., Zeng M., Liao H., Chen H., et al., 2021; Vicente-Tejedor J., Marchena M., Ramírez L., García-Ayuso D., Gómez-Vicente V., Sánchez-Ramos C., de la Villa P. & Germain F., 2018). This research, mirroring modern lifestyles, accurately portrays the detrimental effects of blue light on human eyes, emphasizing its potential toxicity to ocular health. The utilization of a stable and reproducible low-light chronic photodamage animal model offers valuable insights for investigating chronic retinal light damage and retinal degeneration.

3.3 Photophobia and Migraines

The widespread use of LED-backlit Visual Display Terminals (VDTs) rich in blue light has heightened human eye exposure. Intrinsically photosensitive Retinal Ganglion Cells (ipRGCs), sensitive to 460-480 nm blue light, regulate hypothalamic signaling and physiological processes. Zivcevska et al. (2018) found that blue light stimulation may raise photophobia risk, linked to ipRGC activation and trigeminal nerve pathway interaction, suggesting ocular stimulation's role in migraines (Antemie R.-G., Samoilă O.C. & Clichici S.V., 2023). Retinal and trigeminal nerve signaling reinforce each other. Migraine case studies confirm excessive trigeminal nerve stimulation enhances light sensitivity and visual cortex activity, mediated by ipRGC-trigeminal nerve interaction at the posterior thalamus (Aldrich A., Hibbard P.B. & Wilkins A.J., 2019).

Zivcevska et al. (2018) assessed normal subjects' visual discomfort under monocular and binocular vision, maintaining retinal stimulation (using 2.5% phenylephrine). Blue and red light stimuli were used, considering ipRGCs' characteristics. Consistent with previous studies, subjects showed lower sensitivity to red light, while blue light, even at lower intensities, induced visual discomfort more readily. Exploring blue light's impact on health and developing protective strategies is crucial.

4. The Impact of Blue Light Exposure on Sleep

4.1 Suppression of Melatonin Secretion

Intrinsically photosensitive Retinal Ganglion Cells (ipRGCs) regulate circadian rhythms and other physiological processes via hypothalamic signaling. Long-term blue light exposure impairs ipRGC signaling pathways (Ziółkowska N., Lewczuk B., Szyryńska N., Rawicka A. & Vyniarska A., 2023). Animal studies show that prolonged LED light exposure causes mitochondrial damage, reduced dendritic arborization in ipRGCs, and other retinal damage. Blue light (450-500 nm) is crucial for maintaining human circadian rhythms, with inadequate or excessive exposure disrupting them, leading to sleep issues, seasonal affective disorders, and memory/cognitive impairments (Mure LS., 2021).

Furthermore, nighttime LED blue light exposure inhibits melatonin secretion, disrupting biological rhythms (Ward E.M., Germolec D., Kogevinas M., McCormick D., Vermeulen R., & Anisimov V.N., 2019). This occurs through alterations in ipRGC signal transduction in the Suprachiasmatic Nucleus (SCN), the mammalian circadian pacemaker, affecting various physiological functions. Melatonin, an SCN-mediated hormone, promotes sleep. The circadian clock relies on light cues to synchronize endogenous rhythms with external cycles. Thus, nighttime artificial light exposure can disrupt circadian rhythms and clock genes, causing physiological homeostasis issues (Tahir M.J., Malik N.I., Ullah I., Khan H.R., Perveen S., Ramalho R., Siddiqi A.R., Waheed S., Mohamed Shalaby M.M., de Berardis D., et al., 2021), supported by animal studies (Theruveethi N., Bui B.V., Joshi M.B., Valiathan M., Ganeshrao S.B., Gopalakrishnan S., Kabekkodu S.P., Bhat S.S. & Surendran S., 2022).

4.2 Sleep Disorders

Multicolor light intensity significantly correlates with nighttime melatonin suppression, crucial for sleep quality. Circadian rhythm, particularly melatonin secretion, aids sleep. Exposure to 1000 lux indoor artificial light for 1 hour reduces melatonin to daytime levels, while even low-intensity light can awaken individuals, with high-intensity lighting having the greatest impact (Wahl S, Engelhardt M, Schaupp P, Lappe C & Ivanov IV., 2019).

Blue light, at equal photon density, suppresses melatonin twice as much as green light, highlighting its profound influence on circadian rhythms. Blue light inhibits sleep-related delta waves and enhances alertness-related alpha waves, suggesting adverse effects on sleep stability. While daytime suppression by natural or indoor light is beneficial, nighttime exposure differs. Low indoor light (<200 lux, even 3 lux) can disrupt circadian rhythms, causing sleep disorders. Wahnschaffe et al. (2013) found that 500 lux blue light 30 minutes before bedtime delayed REM sleep onset by 30 minutes.

Melanopsin in ipRGCs is highly sensitive to blue light, especially in the evening and night. Even low-intensity blue light from smartphones or e-readers can disrupt circadian rhythms and sleep. Given the widespread use of smartphones, prolonged screen exposure may further reduce sleep duration and quality.

4.3 Sensitivity to Blue Light Exposure Across Different Age Groups

In examining the health impact of blue light, excessive electronic display usage across age groups emerges as a key driver of glaucoma incidence. Glaucoma, a neurodegenerative disorder, manifests as progressive optic nerve and retinal nerve fiber degeneration (Ahn SH, Suh JS, Lim GH & Kim TJ., 2023). While aging is traditionally implicated, surveys reveal a significant rise in glaucoma among 10-29-year-olds, threatening the quality of life.

Besides diet and inactivity, excessive electronic media use among youths elevates glaucoma risk due to sleep disorders and insomnia. Poor posture, cortisol dysregulation causing intraocular pressure rise, and hypoxia from sleep apnea directly harm the optic nerve, fostering glaucoma (Sun C., Yang H., Hu Y., Qu Y., Hu Y., Sun Y., Ying Z. & Song H., 2022). Blue light from screens adversely affects retinal ganglion cell mitochondria, damaging lutein and cytochrome c oxidase, and promoting ROS production (Marek V, Mélik-Parsadaniantz S, Villette T, Montoya F, Baudouin C, Brignole-Baudouin F, et al., 2018)

In retinal ischemia, refractive errors, and oxidative stress, blue light-induced ROS overproduction and mitochondrial DNA damage trigger cell death pathways, ultimately causing vision loss. Blue light triggers apoptosis and necrosis in retinal cells, aggravating glaucoma onset and progression. Therefore, intensified research on the trend of earlier glaucoma onset is crucial for developing preventive strategies.

5. The Impact of Blue Light Exposure on Other Physiological Health Aspects

5.1 Skin

Regarding light's effects on the human body, skin and eyes, as primary radiation recipients, warrant special attention. Blue light, with its potent penetration, reaches depths of 0.07-1mm in skin, significantly affecting it. This light activates melanopsin, triggering TRP ion channels and CAMKII, altering gene transcription (Hiramoto K., Kubo S., Tsuji K., Sugiyama D. & Hamano H., 2023; Regazzetti C, Sormani L, Debayle D, Bernerd F, Tulic MK, De Donatis GM, Chignon-Sicard B, Rocchi S & Passeron T., 2018). Moreover, blue light diminishes keratinocyte clock gene per1 transcription, implying skin cells regulate clock genes in response to light, and nighttime blue light exposure may disrupt skin cell repair mechanisms (Das A., Sil A., Kumar P. & Khan I., 2023). Experimental studies indicate prolonged blue light exposure can induce skin carcinogenesis, enhancing cell proliferation markers and inflammatory cell migration, contrasting with green or red LED light. Hence, blue light's impact on skin health demands further research and protective measures.

5.2 Mental Health

Epidemiological studies establish a strong correlation between circadian rhythm disruptions and heightened risks of diabetes, cognitive/affective disorders, and cancers linked to emotional/psychological health (Fan B., Zhang C.X., Chi J., Liang Y., Bao X.L., Cong Y.Y., Yu B., Li X. & Li G.Y., 2022). Bipolar disorder's emotional fluctuations are closely tied to circadian rhythm disturbances, supported by genetic associations with specific circadian genes (Meléndez-Fernández O.H., Liu J.A. & Nelson R.J., 2023). For manic patients, dark environments may stabilize mood. Melatonin agonists aim to stabilize circadian rhythms, while blue light-blocking treatments like amber glasses significantly improve sleep quality. Bright light therapy's effects on mood and physiology remain under investigation. Bedtime smartphone use adversely affects mood, sleep, memory, and attention, emphasizing the importance of proper lighting for circadian synchronization and overall health.

6. Blue Light Exposure: Protective Measures and Recommendations

6.1 Adjusting Light Sources and Usage Habits

To minimize blue light exposure, selecting light sources with low emissions is crucial. Consumers should prioritize products with low blue light radiation, such as warm white LED lamps. For home and workplace lighting, soft, evenly distributed light should be used to prevent eye irritation. Furthermore, limiting usage duration of VDTs like computers and smartphones is key. Regular breaks away from blue light sources allow eyes to rest, and proper scheduling of work and leisure reduces excessive VDT use, safeguarding eye health.

6.2 Implementing Physical Protective Measures

Physical protection, such as blue light blocking glasses, is essential for reducing blue light exposure. These glasses filter out most blue light using specialized lens materials, minimizing eye irritation and damage. Consumers should opt for trusted brands to ensure product quality. Additionally, applying blue light filters to screens reduces light intensity and eye strain. Advancements in screen technologies, like blue light filtering displays, further mitigate blue light's harmful effects on eyes.

6.3 Technological Innovations and Applications

Technological innovations promise significant advances in addressing blue light exposure. Key is the development of intelligent lighting systems that auto-adjust brightness and color temperature based on environmental and user needs, ensuring optimal illumination while minimizing harmful blue light effects. For instance, smart lighting adapts to time and weather, fostering comfortable environments. Additionally, optimizing visual displays is crucial. Advanced OLED and QLED technologies reduce blue light emissions, while optimized user interfaces with larger fonts and clearer icons minimize prolonged screen use, thereby reducing blue light exposure.

6.4 Establishing Health Education and Monitoring Systems

Strengthening health education and establishing monitoring systems are long-term protective measures. Disseminating knowledge about blue light hazards and protective strategies through media, schools, and communities enhances public awareness. Public awareness campaigns can educate the public on the ocular impacts of blue light and available protective measures. Schools should intensify education on electronic device use, guiding students on proper VDT usage to safeguard eye health.

Concurrently, regular monitoring and assessment of blue light exposure in targeted populations are essential. For instance, regular eye examinations for VDT-intensive workers can assess exposure levels and implement protective measures accordingly. Establishing a long-term monitoring system for blue light exposure can identify and mitigate exposure risks in a timely manner, informing strategic policies to minimize adverse effects.

7. Conclusion and Outlook

This article summarizes the essentials of blue light, its sources, and its growing public health implications, particularly in the context of the COVID-19 pandemic and the rise in indoor VDT use. While the potential ocular surface and retinal hazards of blue light have garnered significant attention, the underlying mechanisms remain unclear. As eye diseases are multifactorial, elucidating the precise cellular and physiological mechanisms of blue light's ocular harm through cytological, animal, and epidemiological studies is paramount. Moreover, blue light's impact on circadian rhythms, mood, and skin health cannot be overlooked. Preventing blue light's negative effects requires personal habit modifications, dietary adjustments, and medical interventions. The disruption of circadian rhythms by modern technologies and lifestyles necessitates societal awareness and transformation to mitigate health risks. Future research must delve deeper into blue light's mechanisms to provide a robust scientific basis for health protection strategies.

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