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The Effect of Artificial Light Pollution on Circadian Rhythm

Yaobing Chen[1*], Wingfong He[1]

[1]*Shenzhen College of International Education, Shenzhen, China*
**Corresponding Author. Email: s23546.chen@stu.scie.com.cn*

Abstract: Circadian rhythms are imperative biological processes that allow organisms, including animals and plants, to synchronize with Earth's day-night cycle and to control numerous physiological mechanisms inside them. In mammals, the suprachiasmatic nucleus (SCN) in the hypothalamus acts as a central clock, while the peripheral clock, which is outside of the central clock, regulates the specific local functions. Within the circadian clock, the key genes like BMAL1, CLOCK, PER, and CRY coordinate with each other to form a feedback loop. The CCA1, LHY, and TOC1 genes can also form a feedback loop in plants, just like in mammals. However, due to the development of modern cities and urbanization, the widespread use of artificial light has caused severe light pollution, which disrupts the natural circadian rhythm. The source of artificial light pollution (ALP) includes streetlights, indoor and screen lights, industrial lights, etc. The ALP has already affected people worldwide, with more than 80% of the world's population experiencing it, leading to severe impacts. For instance, it can adversely affect people's physical and mental health, as well as disrupt the normal secretion of hormones such as melatonin and cortisol. Therefore, understanding the effects of ALP on circadian rhythm is important to address the growing concern of environmental impact and public health today.

Keywords: Circadian rhythm, Artificial light pollution, Sleep cycle

1. Introduction

Circadian rhythms refer to the internal biological processes that align with the Earth's 24-hour day-night cycle. These rhythms are present in all living organisms, including humans and plants, and are essential for regulating a wide range of physiological functions [1]. For instance, in humans, it promotes wakefulness during the day and provides the drive to sleep at night by using melatonin— a hormone that prompts sleepiness. Moreover, it can also contribute to the coordination of metabolism to maintain the homeostasis in the body by controlling the secretion and release of insulin, glucagon, and cortisol, which is known as the "hormone of stress" [2]. The circadian system also plays a crucial role in the immune system, as many immune cells exhibit circadian variations in their activity. Furthermore, the circadian clock can regulate the cognitive system, which not only improves the concentration through the release of neurotransmitters like dopamine but also regulates and consolidates the memory during sleep [3]. In mammals, the core of the circadian clock is the suprachiasmatic nucleus (SCN), located in the hypothalamus, which is known as the "central clock" and acts as the master pacemaker, receiving light input from the retina and coordinating the activities of cells and tissues throughout the body. In addition to the central clock, there are "peripheral clocks" found in various organs and tissues, such as the liver and pancreas, which regulate local physiological

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processes, including metabolism. The SCN regulates and adjusts the internal body system in response to external signals, such as light. On the other hand, the peripheral clock responds to internal signals like body temperature, blood glucose concentration, and hormones [4]. At the molecular level, the circadian clock is driven by a tightly regulated transcriptional-translational feedback loop involving several core genes, including BMAL1, CLOCK, PER, and CRY. The BMAL1 is a core component in the functioning of the clock, as it forms a heterodimer with the CLOCK protein and binds to specific DNA sequences called E-box elements in the promoters of target genes (including the PER and CRY genes), hence activating their transcription. After the translation, PER and CRY proteins accumulate in the cytoplasm and later translocate into the nucleus, where they inhibit the activity of the BMAL1–CLOCK complex, thus completing the negative feedback loop [5]. As for the clock in plants, genes such as CCA1 and LHY act as key regulators in the morning, suppressing the expression of other genes such as TOC1, which in turn promotes the expression of CCA1 and LHY during the evening. This cyclical regulation forms a feedback loop analogous to that in mammals [6].

However, with the rapid expansion of the modern cities, light pollution, also known as artificial light pollution (ALP), has now become a major disruptor of the circadian rhythm. ALP refers to the excessive, misaligned, or unnecessary use of artificial light, particularly at night, and it disrupts the natural darkness by introducing light into environments where it is not needed [7]. The circadian system, which depends heavily on predictable cycles of light and darkness, is particularly vulnerable to such disturbances. Common sources of light pollution include streetlights at night for cars during the drive and uncontrolled upwards light splitting, even though these lights are vital for safety, but their disruption to natural darkness and interference with nocturnal wildlife are unneglectable [8]. Industrial light, as the major culprit of light pollution, is often seen in high-density areas such as factories and construction sites. These lights are typically unshielded, intensely bright, and operate continuously, and they not only affect the nearby residents but also impact the quality of astronomers and stargazers. Moreover, even indoor lighting and electronic screen exposure—though seemingly minor in scale—pose significant risks due to their ubiquity. The blue light emitted by electronic screens such as phones and computers can suspend the secretion of melatonin, therefore causing people's delay of circadian cycle [9]. What's more, the populated area with high-intensity screen lights being used can have consequences as an overall light-saturated environment. Global prevalence of light pollution is extensive, affecting a large portion of the world's population. According to a study published in Science Advances, more than 80% of the global population lives under light-polluted skies. Nearly 80% of the population in North America and 60% of the population in Europe are unable to see the Milky Way due to light pollution [10, 11]. ALP impacts people's normal secretion patterns of the hormones and helps regulate sleep-wake cycles [12]. Furthermore, the breakdown of the dark cycle will also interfere with the normal secretion patterns of other hormones. For example, cortisol, a stress hormone, typically follows a specific diurnal pattern. Abnormal cortisol levels due to ALP can lead to increased stress responses, reduced stress resilience, and potential long-term health issues related to chronic stress [13].

2. Mechanisms of artificial light pollution on circadian rhythm

Intrinsically photosensitive retinal ganglion cells (ipRGCs), the important cells within our eyes, play an important role not only in regulating our circadian rhythm but also in detecting and adapting to external light changes. IpRGCs comprise 3-5% of retinal ganglion cells, which can express the melanopsin that is often cooperated with rods and cones and is essential for our non-image-forming vision. As for the key function of ipRGCs, the first one is the synchronization between circadian rhythm and the external light-dark cycle. After receiving the light, ipRGCs can directly project to the ventrolateral part of the SCN, which is located in the hypothalamus. Then the SCN can address this light information and trigger the synchronizing neuron to generate electrical impulses, which can

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interact with the peripheral clock and regulate the hormone level in our body. Another function of ipRGCs is that they can interact with the nearby cells; for instance, they can coordinate with the dopaminergic amacrine (DA) cells, stimulating them to release dopamine into the retina [7]. However, the interaction of artificial light (the abundant blue light source) can stimulate the melanopsin within ipRGCs at the wrong time, thus interrupting our circadian clock. Since the melanopsin has a spectral sensitivity peak at 480nm, it can interact and respond strongly to the blue light that is emitted by artificial light [14]. Thus, this continuous or misaligned light can arouse and raise the level of corticosterone, postponing the sleep, impairing the SCN signaling, and eventually causing the circadian misalignment [2]. And this interruption can lead to several physiological consequences, such as insomnia, daytime sleepiness, a decrease in metabolic efficiency, a disturbance of glucose homeostasis, etc.

Artificial light at night can significantly suppress the melatonin secretion by sending signals to the pineal gland. When exposed to under artificial light during nighttime, the SCN will address the light signal that it received from ipRGCs and send signals via sympathetic nerves to the pineal gland (the gland that releases melatonin), hence inhibiting the expression of melatonin [15]. According to a study, even dim light exposure at night can significantly reduce melatonin levels. Among all wavelengths, blue light (approximately 450–480 nm) has the strongest suppressive effect on melatonin secretion [14]. This wavelength range, commonly emitted by electronic screens and LED lighting, is particularly disruptive to the body's internal clock. It can effectively inhibit the secretion of melatonin and has the most substantial impact compared to the other wavelengths of light. Melatonin suppression can lead to numerous physiological impacts. One of the most immediate effects is sleep disruption [14]. A decrease in melatonin secretion can cause sleep delay, resulting in poor sleep quality and shorter sleep duration. This can eventually lead to various sleep-related diseases, such as sleep disorders, insomnia, and hypertension. Moreover, it can also have impacts on metabolism. Since the suppression of melatonin can lead to the disrupted circadian rhythm, it may also cause disorder in the peripheral clock, hence interrupting the homeostasis, like normal and constant blood glucose concentration, and causing the metabolic dysregulation. And increasing the risks of having diabetes, hypertension, and obesity [16]. Melatonin also plays an important role in the human immune system, as it can strengthen the secretion and activity of the immune cells, including phagocytes and lymphocytes. And it can also prompt the production of pro-inflammatory cytokines [17]. Therefore, decreasing melatonin secretion can result in weak immune defense, uncontrolled inflammatory response, and increasing the risk of cardiovascular diseases.

Disruption in sleep-wake cycles is a common consequence of exposure to artificial light at night, particularly in the urban areas where ALP is severe and widespread. Due to the suppression of melatonin, which is caused by the exposure under the ALP, the body's natural sleep-wake cycle will be delayed, causing the later sleep onset and the reduced sleep duration. Furthermore, light exposure at night can also lead to sleep fragmentation, damaging the cycles of SWS (slow-wave sleep) and REM (rapid eye movement) sleep. These two types of sleep are crucial for the human body, as SWS is considered an important part of homeostatic regulation and the most restorative sleep period [18]. And during the REM sleep stage, the brain can adjust its synapses, thus improving memory and learning abilities, and it has also been proved that REM sleep can help to reduce the risk of dementia [19]. Urban areas usually have a higher proportion of ALP, which can lead to an increase in insomnia and clock disorder in urban populations. According to recent research, due to the high level of ALP, the urban population generally has poor sleep quality and higher rates of sleep disorders compared to the rural population. Therefore, the increase in sleep disorders in urban areas brings some subsequent impacts on urban populations, such as the high level of affection and anxiety disorders. In fact, one study reported a 21% increase in the prevalence of anxiety disorders among urban residents, underscoring the significant psychological impact of ALP on urban populations [20].

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Moreover, ALP can induce molecular disruptions in the expression of circadian clock genes. The intricate transcriptional-translational feedback loop involving BMAL1, CLOCK, PER (Period), and CRY (Cryptochrome) is essential for maintaining circadian rhythmicity. However, exposure to ALP, especially at night, leads to the alteration in expression patterns of these core clock genes [5]. And such dysregulation leads to circadian disruption, which means that the internal rhythms will be desynchronized with the external environment, resulting in sleep disorder. Long-term exposure to ALP can result in epigenetic modifications, including DNA methylation and histone modifications, particularly in the promoter regions of circadian clock genes. These changes can persistently alter gene expression without changing the underlying DNA sequence, leading to long-lasting circadian misalignment [21]. Over time, this misalignment can lead to lots of health problems and disrupts the synchronization between central and peripheral clocks. For instance, the interruption of ALP can cause metabolic dysregulation, destroying the balanced homeostasis in the liver. Moreover, in the heart, the circadian clock influences cardiac function by regulating the expression of genes involved in heart rhythm and systolic and diastolic function [22].

3. Consequences of artificial light pollution in health and physiology

Metabolism disorders are a significant example of the adverse health effects brought by ALP, primarily due to the disruption of the body's natural circadian rhythm. This disruption affects various key physiological processes, including glucose and lipid metabolism, insulin sensitivity, and hormone regulation [12]. Exposure to light at night, especially in the evening, can impair glucose homeostasis by disrupting the body's natural insulin sensitivity and glucose uptake mechanisms. One of the reasons for this is because of the suppression of melatonin, which is the central mediator for the expression of insulin. Moreover, the mutation of the insulin receptor caused by the disruption of glucose and lipid metabolism also leads to insulin resistance [9]. As circadian rhythms shift due to prolonged nighttime light exposure, individuals are more likely to stay up late, which can disturb natural feeding cycles. By midnight, food consumed earlier in the evening is typically digested, the stomach is empty, insulin levels drop, and the hunger hormone ghrelin is released, increasing the urge to eat [23]. Such behaviors may result in late-night snacking, contributing to excessive caloric intake and weight gain, especially since metabolism slows during sleep. Over time, this pattern may lead to obesity, digestive dysfunction, and increased risk of type 2 diabetes. Obesity also exerts physical pressure on the respiratory system, particularly the trachea, which can result in obstructive sleep apnea (OSA)—a sleep disorder characterized by repeated airway collapse during sleep. OSA disrupts sleep quality, causing frequent awakenings and daytime fatigue. Additionally, light exposure activates ipRGCs, which innervate the hypothalamus and influence glucose metabolism by affecting brown adipose tissue (BAT) thermogenesis. This neural pathway can decrease glucose tolerance by blocking adaptive thermogenesis in BAT [24, 25]. Moreover, neurocognitive and psychological effects are also brought on by the light at night (LAN). Research suggests a potential link between LAN and neurodegenerative changes, possibly accelerating aging and increasing the risk of diseases such as Alzheimer's. Melatonin suppression is thought to interfere with the regulation of pathological proteins involved in neurodegeneration, contributing to cognitive decline and diminished brain function over time [26].

Light at night disrupts the body's natural circadian rhythm, which is crucial for maintaining mental health, primarily through melatonin, a hormone that regulates sleep and mood. Research has shown that for individuals exposed to high levels of light at night, the risk of depression increased by 30%, whereas those who are exposed to ample natural light during the day experience a 20% reduced risk [27]. Poor sleep quality resulting from nighttime light exposure can reduce concentration and increase anxiety in the morning of the next day. ALP-induced circadian disruption also affects dopamine function. Dopamine is involved in reward processing, motivation, and motor control. Dysregulation

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of dopamine is associated with mood disorders and cognitive impairments. Higher serotonin levels are often associated with improved mood and reduced symptoms of depression. Serotonin acts as a natural mood booster, helping to alleviate feelings of sadness and anxiety. In studies, serotonin levels can peak during the night, particularly around 9-11 PM, especially in brain regions like the hypothalamus and hippocampus. When this pattern is disrupted, it may contribute to symptoms of anxiety and depression as part of a broader neuroendocrine imbalance [27]. As night-shift workers as an example, up to 33% of the night-shift workers have experienced depression, significantly higher compared to the day-shift workers [28]. Chronic ALP exposure disrupts hormone secretion, such as melatonin. This disruption can lead to poor sleep quality and elevated stress levels. Poor sleep quality not only increases the inflammation but also elevates blood pressure. The elevated blood pressure is maintained at a high rate during both sleep and wake periods, which increases the risk of coronary heart disease (CHD) [29]. Exposure to artificial light at night during sleep can impair cardiac autonomic function, as evidenced by reduced parasympathetic activity and increased sympathetic activity. This imbalance can lead to increased heart rate variability (HRV) and stress on the cardiovascular system, which increases cortisol levels and heart rate. Such physiological stressors can delay reflex responses and reduce the body's ability to react instinctively. Furthermore, melatonin is a key regulator of proinflammatory genes (e.g., TNF-α, IL-6, COX-2); it can inhibit the nuclear factor kappa-light-chain-enhancer of activated B cells (NF-κB) pathway. Reduction of melatonin levels fails to suppress NF-κB translocation to the nucleus, leading to elevated expression of inflammatory cytokines and adhesion molecules. For example, in conditions like sepsis, melatonin has been shown to reduce inflammatory biomarkers as an adjunct therapy [30].

4. Conclusion

This essay examined the profound effects of ALP on circadian rhythms and its wide-ranging implications for human health and urban ecosystems. Key findings reveal that ALP disrupts the natural synchronization of biological clocks, leading to sleep disorders, metabolic dysfunctions, and psychological disorders. The suppression of melatonin and misalignment of circadian rhythms are central mechanisms behind these adverse effects. Future research should focus on elucidating the molecular and systemic impacts of ALP, particularly its long-term influence on epigenetic modifications and circadian gene expression. Investigating innovative solutions, such as light management technologies and urban designs that mitigate ALP, is essential to restore harmony between human activities and natural cycles. Moreover, public awareness and policy changes are urgently needed to address this growing issue. Furthermore, educating communities about the risks associated with ALP and advocating for regulations on artificial lighting can help reduce its prevalence. Finally, by integrating chronobiological principles into urban planning and healthcare systems, we can create environments that promote better sleep quality, mental health, and metabolic balance, ultimately fostering healthier and more sustainable cities.

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