Smart Lighting and Cancer Prevention: Can Technology Help Reduce Health Risks?

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Abstract
Artificial light at night (ALAN) has become an inescapable component of modern life, shaping environments in homes, workplaces, and urban spaces. While technological advances in lighting have improved visibility and safety, growing epidemiological evidence links chronic exposure to ALAN with increased cancer risk, particularly hormone-sensitive cancers such as breast and prostate cancer. This review explores the biological mechanisms underlying this association, focusing on circadian rhythm disruption, melatonin suppression, and light-induced oxidative stress and DNA damage. We critically examine epidemiological studies that reinforce these mechanisms and highlight the role of smart lighting technologies in mitigating these risks. Smart lighting systems—featuring tunable LEDs, sensors, and adaptive control—offer a promising solution by aligning artificial lighting with natural circadian patterns. This review evaluates how circadian-optimized lighting designs can preserve melatonin levels, reduce biological stressors, and potentially serve as a non-invasive cancer prevention strategy. Additionally, we address the challenges of implementation, the limitations of current research, and the need for interdisciplinary studies to validate long-term health outcomes. Ultimately, this review emphasizes the importance of leveraging smart lighting innovation not only for energy efficiency and comfort but also as a proactive tool in public health strategies against cancer.

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1. Introduction

In our modern, urbanized world, artificial lighting has become an integral part of daily life, illuminating homes, workplaces, and cityscapes. While this technological advancement has extended productive hours and enhanced safety, it has also led to increased exposure to artificial light at night (ALAN), raising concerns about potential health implications [1]. Epidemiological studies over the past few years have increasingly linked ALAN exposure to an elevated risk of various cancers. Similarly, a study reported that both indoor and outdoor ALAN exposures were linked to increased breast cancer risk [2]. These associations are thought to be mediated by the suppression of melatonin, a hormone that regulates circadian rhythms and possesses anti-cancer properties. The International Agency for Research on Cancer (IARC) has classified night shift work, which often involves exposure to high levels of ALAN, as a probable carcinogen. Given the pervasive nature of artificial lighting and its potential health risks, there is a pressing need to explore technological innovations that can mitigate these effects. Smart lighting systems, which can adjust intensity and spectral composition based on time of day and occupancy, offer a promising avenue for reducing ALAN exposure and its associated health risks [3].

This review aims to synthesize recent epidemiological evidence linking ALAN to cancer risk and to explore how smart lighting technologies can be leveraged as a preventive strategy. By examining the intersection of lighting technology and public health, we seek to highlight opportunities for innovation that promote well-being in our increasingly illuminated world. The increasing prevalence of artificial light in modern environments—ranging from homes and offices to outdoor urban spaces—necessitates a closer examination of its long-term health effects. Over the past several years, scientific and public health communities have turned growing attention to the role of ALAN as a potential environmental risk factor for cancer [4]. In light of this emerging evidence, the scope of this review focuses on understanding the interplay between artificial lighting, circadian disruption, and cancer risk, while also investigating the role of smart lighting technologies in mitigating these risks.

2. Biological mechanisms linking light exposure to cancer

The association between artificial light exposure—particularly at night—and cancer development is increasingly understood through its impact on key physiological systems as shown in Figure 1. Central to this is the disruption of circadian rhythms and the suppression of melatonin, both of which play vital roles in regulating cellular function, protecting DNA integrity, and modulating tumor growth [5]. This section explores how these biological mechanisms are influenced by light and contribute to cancer risk. The circadian clock is an intrinsic time-keeping system that governs numerous physiological processes, including cell cycle progression, DNA repair, and programmed cell death (apoptosis) [6]. These functions are tightly regulated in a 24-hour cycle to ensure genomic stability and controlled cell proliferation. When this rhythm is disrupted—such as through nocturnal light exposure—it can lead to misregulated gene expression, impaired DNA repair mechanisms, and abnormal cell division, increasing susceptibility to malignant transformation [7].

Artificial light, particularly during the night, disrupts the circadian system by altering the normal pattern of light and darkness that the body relies on to synchronize its internal clocks. The suprachiasmatic nucleus (SCN) in the brain's hypothalamus receives input from light-sensitive retinal cells and coordinates peripheral clocks throughout the body [8]. Exposure to light at inappropriate times, especially blue-enriched light, can desynchronize these clocks and shift or dampen circadian rhythms [9]. Melatonin plays a key protective role in human health. Beyond regulating sleep-wake cycles, melatonin functions as a potent antioxidant and possesses oncostatic (cancer-suppressing) properties. It scavenges free radicals, enhances DNA repair, and inhibits tumor-promoting pathways including estrogen receptor signaling and angiogenesis [10]. However, melatonin production is highly sensitive to light, especially short-wavelength blue light (~460–480 nm), which is prevalent in many modern lighting sources such as LEDs and electronic screens. Even low levels of blue light at night have been shown to suppress melatonin synthesis, reducing its circulating levels and thereby weakening the body's natural defense against oxidative damage and tumor development [11].

Numerous animal and human studies over the past five years have confirmed that melatonin suppression correlates with increased tumor growth in hormone-sensitive tissues. For example, women exposed to higher levels of ambient light at night exhibit lower melatonin levels and a higher risk of estrogen receptor-positive breast cancer [12]. Furthermore, experimental studies have demonstrated that maintaining melatonin levels—either through darkness, light filtering, or melatonin supplementation—can inhibit tumor progression and improve treatment responses, highlighting the hormone's therapeutic potential [13]. Prolonged exposure to artificial light, especially during the biological night, can also contribute to oxidative stress and DNA damage, both of which are critical events in the initiation and progression of cancer. One of the underlying pathways involves the generation of reactive oxygen species (ROS)—unstable molecules that can damage cellular components such as DNA, proteins, and lipids [14].

Under normal physiological conditions, the body maintains a balance between ROS production and antioxidant defenses. However, disruption of circadian rhythms and suppression of melatonin, both of which are consequences of nighttime light exposure, can tip this balance [15]. Melatonin is a powerful antioxidant that directly neutralizes ROS and enhances the activity of other antioxidant enzymes. Its suppression leaves cells more vulnerable to oxidative damage. Moreover, oxidative stress caused by ALAN is not confined to one tissue type; it has been observed in the mammary glands, brain, liver, and prostate, suggesting a systemic vulnerability [16]. This is particularly concerning given the widespread exposure to artificial lighting in residential and occupational settings. Emerging evidence also links oxidative stress to epigenetic modifications, such as DNA methylation changes and histone modifications, which can silence tumor suppressor genes and activate oncogenes. This epigenetic instability further contributes to cancer risk in individuals with prolonged light exposure, particularly in high-risk populations such as shift workers [17].

This schematic (Figure 1) illustrates the potential pathways through which artificial light exposure at night (ALAN) contributes to cancer development and how smart lighting systems may help mitigate these risks. Exposure to ALAN disrupts normal biological processes through three major mechanisms: (1) Circadian Rhythm Disruption, which interferes with the regulation of the cell cycle, DNA repair, and apoptosis; (2) Melatonin Suppression, where blue light inhibits nocturnal melatonin secretion, thereby reducing its antioxidant and oncostatic functions; and (3) Oxidative Stress and DNA Damage, as prolonged light exposure increases reactive oxygen species (ROS), leading to genotoxic effects. These pathways collectively elevate cancer risk, particularly for hormone-sensitive and other solid tumors. Smart lighting, incorporating tunable LEDs, automated sensors, and circadian-adaptive control, is proposed as a preventive strategy. By aligning artificial lighting with natural light cycles—reducing blue light exposure at night and supporting melatonin production—smart lighting systems may preserve circadian health and reduce cancer risk in domestic, occupational, and urban environments [18].

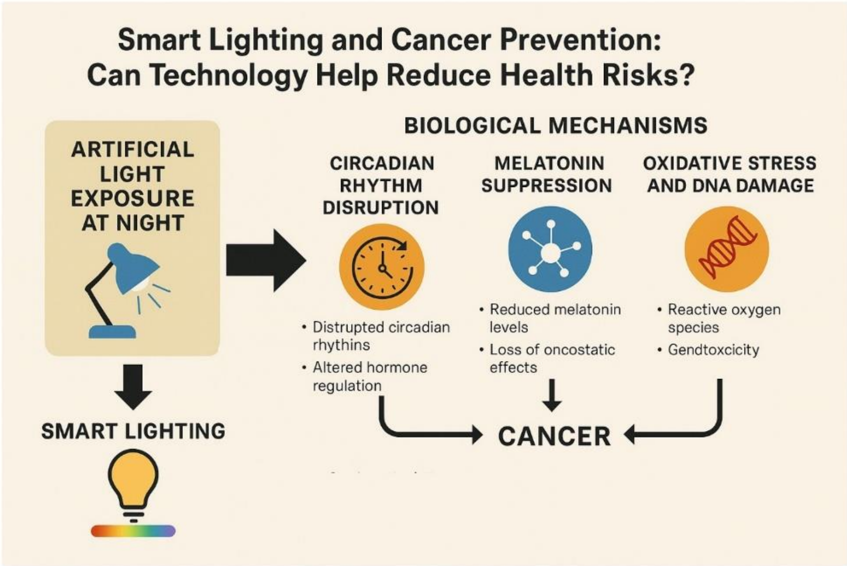

Fig 1: Mechanisms linking artificial light at night (ALAN) to cancer risk and the potential preventive role of smart lighting.

Exposure to artificial light during nighttime hours disrupts key biological processes through three primary mechanisms: circadian rhythm disruption, melatonin suppression, and increased oxidative stress leading to DNA damage. These disruptions are associated with elevated risks of hormone-sensitive and other cancers [19]. Smart lighting systems—equipped with tunable LEDs, adaptive control, and circadian-aware programming—are designed to minimize ALAN-related health impacts. By reducing blue light exposure at night, supporting natural circadian rhythms, and preserving melatonin production, smart lighting offers a non-invasive strategy to potentially reduce cancer risks in modern environments [20].

3. Epidemiological evidence: ALAN and cancer risk

Recent epidemiological studies have reinforced the association between exposure to ALAN and an increased risk of breast cancer, particularly among night shift workers. A study found that persistent night shift work is associated with a higher risk of breast cancer, especially in hormone receptor-positive subtypes such as estrogen receptor-positive (ER+), progesterone receptor-positive (PR+), and HER2-positive (HER2+) tumors. These findings suggest that circadian disruption caused by ALAN may influence hormone-sensitive pathways, contributing to breast carcinogenesis [21, 22].

Emerging research has begun to explore the association between ALAN exposure and colorectal cancer risk. A study conducted in Spain reported that participants with the highest exposure to blue light at night had a 60% higher risk of developing colorectal cancer compared to those with lower exposure levels [23]. This finding underscores the potential impact of ALAN, particularly blue light, on colorectal carcinogenesis. While direct studies linking ALAN to liver cancer are limited, evidence suggests that night shift work may contribute to hepatic metabolic dysfunction. Studies have demonstrated a positive correlation between night shift work and elevated liver enzymes, indicative of hepatic metabolic dysfunction, potentially increasing the risk of hepatocellular carcinoma (HCC) [24] related to non-alcoholic fatty liver disease (NAFLD) [25]. The relationship between ALAN and endometrial cancer remains less clear. A study within the NIH-AARP Diet and Health Study cohort did not find a significant association between outdoor ALAN exposure and endometrial cancer risk. However, the study acknowledged limitations, including the inability to account for indoor light exposure and other potential confounding factors, suggesting that further research is needed to clarify this relationship [26].

4. Smart lighting as a cancer prevention strategy

Circadian-optimized lighting design aims to align artificial lighting with the body's natural biological rhythms, thereby supporting overall health and potentially reducing cancer risk. This approach involves the use of tunable light color temperatures and intensities that mimic natural daylight patterns. For instance, cooler, blue-enriched light during the day can promote alertness, while warmer hues in the evening can facilitate relaxation and melatonin production. Implementing such lighting systems in environments like hospitals has shown promise in supporting circadian rhythms and improving patient outcomes [27]. Melatonin plays a crucial role in regulating sleep-wake cycles and possesses antioxidant properties that may protect against cancer. Exposure to blue light at night can suppress melatonin production, disrupting circadian rhythms and potentially increasing cancer risk. Smart lighting systems can mitigate this by controlling the timing and spectrum of light exposure. For example, reducing blue light exposure in the evening and utilizing warmer hues can help preserve melatonin levels. Studies have demonstrated that adjusting the color and intensity of LED lighting throughout the day can positively impact melatonin rhythms and sleep quality [28].

The integration of smart lighting systems holds significant potential for public health, particularly in mitigating cancer risks associated with circadian disruption. Individuals working night shifts are at increased risk for circadian rhythm disturbances. Implementing smart lighting that simulates natural light patterns can help align their biological clocks, potentially reducing health risks [29]. Older adults often experience disrupted circadian rhythms. Smart home technologies, including adaptive lighting, have been shown to support independent living and improve quality of life among the elderly. Cities with high levels of artificial light at night can benefit from smart lighting solutions that reduce light pollution and align with natural light cycles, thereby supporting the health of urban residents [30]. From an economic perspective, smart lighting systems offer energy savings and potential healthcare cost reductions. For instance, LED smart lighting can reduce energy costs by an average of 70%, with a payback period of approximately seven years. These savings, coupled with the potential health benefits, underscore the value of investing in smart lighting infrastructure [31].

5. Challenges and Limitations:

Despite the promising potential of smart lighting in mitigating circadian disruption and reducing cancer risk, several challenges and limitations must be acknowledged. While numerous epidemiological and experimental studies have established associations between ALAN, circadian disruption, and increased cancer risk, direct clinical evidence connecting smart lighting interventions to reduced cancer incidence is still lacking. Most existing studies focus on short-term physiological benefits, such as improved sleep, mood, or hormonal regulation, rather than long-term oncological outcomes [32].

This gap is partly due to the relatively recent adoption of smart lighting technologies, which means there hasn't been enough time for longitudinal studies to assess their preventive impact on cancer. Moreover, variability in lighting environments, individual light sensitivity, and lifestyle factors make it difficult to isolate the specific effects of lighting systems on cancer risk in diverse populations [33]. The cost and complexity of deploying smart lighting systems remain a major obstacle, particularly in public and low-income residential settings. High-quality tunable LEDs, AI-based control units, and sensor networks require initial capital investment and ongoing maintenance, which may not be feasible for all institutions or households. Additionally, the technical knowledge required for optimal installation and calibration of circadian-friendly lighting is not yet widespread. Many lighting professionals and building designers still lack training in biologically informed lighting design, which is essential to maximize health benefits. In some regions, energy policy and building codes have yet to adapt to the advancements in smart lighting technology, further delaying integration at scale [34].

6. Future perspectives and research directions

As smart lighting technologies continue to evolve, they offer a promising frontier in preventive healthcare—particularly for conditions influenced by circadian biology, such as cancer. However, to fully realize their potential, a coordinated effort across disciplines, sectors, and society is required [35]. Tackling the complex relationship between light exposure and cancer risk demands collaboration between technology developers, biomedical researchers, and epidemiologists. Engineers and lighting designers must work with clinicians and public health scientists to develop systems that are not only functional and energy-efficient, but also biologically appropriate [36]. Long-term, randomized controlled trials and population-based cohort studies are needed to assess the true preventive value of circadian-friendly lighting. This includes tracking health outcomes in environments with smart lighting compared to those with traditional systems, particularly among at-risk groups such as shift workers and urban dwellers [37]. The rise of wearable health technologies—such as smartwatches, sleep trackers, and light sensors—opens the door to personalized light exposure management. When integrated with smart lighting systems, these devices could help tailor indoor lighting to individual circadian rhythms, work schedules, or sleep patterns in real time. For example, wearable data could inform lighting systems when a user is jet-lagged, working a night shift, or experiencing sleep disruptions, prompting dynamic adjustments to support circadian alignment. This personalized, data-driven approach has the potential to maximize both comfort and health benefits [38].

Smart lighting should be viewed not only as a tech innovation, but also as a tool for building sustainable and health-promoting environments. Hospitals, eldercare facilities, and residential complexes can benefit from lighting systems that reduce operational costs while enhancing health outcomes [39]. Integrating circadian lighting into healthcare design aligns with principles of environmental sustainability and preventive medicine, reducing reliance on pharmaceutical sleep aids and improving quality of life, particularly for vulnerable populations. Equally important is raising public awareness about the health risks of poor lighting and the benefits of circadian-friendly design. Educational campaigns can empower individuals to make informed choices—such as limiting screen time before bed, using warmer lighting in the evening, or adopting smart lighting at home [40].

7. Conclusion

The modern world is illuminated around the clock—from homes and offices to hospitals and city streets. While artificial light has revolutionized human productivity and convenience, a growing body of research over the past decade—and especially in the last few years—has drawn attention to its unintended health consequences. Among the most pressing concerns is the disruption of circadian rhythms and melatonin suppression due to artificial light at night (ALAN), both of which have been epidemiologically linked to increased cancer risk, particularly for hormone-sensitive and lifestyle-related cancers.

In this context, smart lighting emerges as a promising, non-invasive strategy to mitigate these risks. With the ability to mimic natural light cycles, regulate blue light exposure, and adapt to individual needs through AI and sensor-based technologies, smart lighting systems can help realign artificial environments with the biological needs of the human body. This offers a tangible, scalable intervention—particularly beneficial for shift workers, the elderly, and urban populations—where traditional medical solutions may fall short. However, unlocking the full potential of smart lighting for cancer prevention will require continued interdisciplinary research, spanning technology development, biomedical validation, and epidemiological analysis. Equally important is a global shift in policy and public awareness, recognizing light not merely as an environmental design element but as a powerful health determinant. Integrating circadian-friendly lighting into everyday life—through smart homes, workplaces, and public infrastructure—could mark a vital step forward in the effort to create healthier, more sustainable living environments. As we move toward a future shaped by both innovation and wellness, embracing intelligent lighting practices may well be one of the most overlooked yet impactful strategies in the fight against cancer.

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