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CIRCAD EFFICIENCY OF LIGHT-EMITTING DIODE RADIATION FOR GENERAL LIGHTING

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Abstract- The article investigates the biological effects of radiation from a light-emitting diode (LED) and traditional light sources with different correlated color temperatures (*CCT*) on the secretion of melatonin. As is well known, melatonin is an extremely important hormone. The irregularity of cycles of change in melatonin concentration can lead to various diseases. A graph of the dependence of the relative biological equivalent on the *CCT* LEDs was built. Increased *CCT* has been shown to reduce melatonin secretion. It is necessary to take into account the danger of biological effects of the emission spectrum of white LEDs in the violet-blue-mid-blue band at (*CCT* > 3500 K). For household LEDs, it is necessary to limit *CCT* to 3500 K.

Keywords: Light-Emitting Diode, Melatonin Secretion, Correlative Color Temperature, Biological Effect, Wavelength, Circadian Efficiency Coefficient.

1. INTRODUCTION

Light is the most important component of the living environment for a person. It serves not only to obtain visual information, but also has a biological effect on human organisms. In the process of evolution, the regular alternation of day and night has become the main factor that controls the biological processes in the human body. In addition to the visual receptors of the eye (cell rods and cones), which provide the receipt and primary processing of information transmitted by light about the environment, there is a third type of receptors that act as sensors for the central "biological clock" of the body. It was discovered recently and is called the circadian cycle receptor [1, 2].

The biological clock manages a number of biological processes in the body. Based on the information about the illumination, the main synchronizer of regulation is the periodic change of day and night. The discovery of receptors for the circadian cycle and the biological effects of light on the human body has changed approaches to lighting requirements. For the characteristics of light quality, new concepts have been introduced, such as the biological activity of light, circadian efficiency, biological equivalent of radiation [3-5]. Up until now there are the large number of articles have been published on the effect of light on the health and well-being of people [1, 2].

Many articles have been published on the effect of light radiation on hormone secretion and related problems in the human body. Melatonin is one of the most important hormones in the human body. Melatonin is a natural chrono biotic which regulates the biorhythms of the human body and participates in the sleep cycle [1]. After the discovery of a new type of receptors in the retina reflecting the biological effects of light on the organism-ganglion cells, it was found that signals generated by light rays entering these cells enter the pineal gland located in the center of the brain [2] and [6-8]. The sensitivity of the new photoreceptor to the wavelength of light rays is different. The effect of the spectral composition of radiation on the secretion of hormone melatonin regulating circadian and neuroendocrine systems of an organism is shown in Figure 1 [9].

As shown in the graph, the attenuation of the secretion of the hormone melatonin reaches a maximum at 464 nm. Figure 1 shows the results of the study in color circles under the influence of radiation of eight wavelengths (440, 460, 480, 505, 530, 555, 575, 600 nm). The study involved 72 healthy individuals. The unpainted circle corresponds to a wavelength of 420 nm. The graph corresponds to a sensitivity curve to the light-sensitive retinaldehyde pigment (vitamin A1) with a maximum spectral sensitivity of 464 nm [10]. The correlation coefficient between the sensitivity of the photosensitive pigment and the decrease in melatonin secretion is quite high (R^2 = 0.91).

It is clear from the graph that monochromatic short wavelengths light rays, unlike light waves with large wavelengths, effectively cause a phase shift of the circadian system and a decrease in melatonin secretion. For example, in luminescent lamps (LL) with a high *CCT*, unlike low *CCT* LL, the maximum radiation falls on the blue part of the spectrum which leads to a strong weakening of melatonin secretion.

However, LL with a high *CCT* has a strong effect on body temperature. An increase in *CCT* in the lamps leads to an increase in blood pressure and reduces the frequency of electroencephalogram. Studies of the effects of pre-bedtime lighting show that a lamp with a high *CCT* in the first half of sleep significantly reduces sleep depth as opposed to a lamp with a low *CCT* [6].

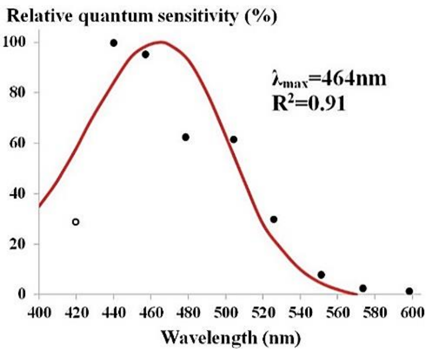

Figure 1. Relative spectrum of attenuation of melatonin secretion [10]

The production of the hormone melatonin synchronizes with the light that affects the person. In case of the light of a certain color does not reach the human eye in the required amount, there is desynchronization of biorhythms, i.e., initially insomnia, fatigue, mood swings, and, as a result, a person has various chronic diseases. The graph in Figure 2 shows that in the evenings the pineal gland actively produces the hormone melatonin.

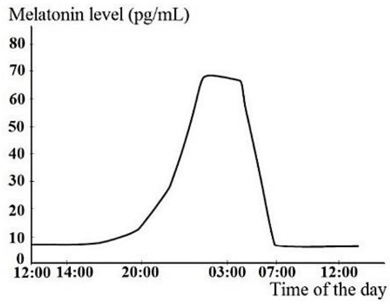

Figure 2. Changes in the concentration of melatonin in the human body at different times on the day [9]

During the deepest sleep at night, approximately at 2 O'clock, there is an increase in melatonin secretion in the blood. At 7 a.m., the concentration of melatonin drops, and during the day its minimum is observed. It has been established that with bright lighting during the day, the secretion of melatonin in the human body decreases, and human activity increases, and when illuminated below the required level, the secretion of melatonin increases and this leads to sleep and a decrease in the activity of the human body. In both cases, the performance of the body is impaired, and body temperature, blood pressure, and pulse rate change.

Taking into consideration that the consequences of changing the level of illumination, the prolonged disturbance of its natural rhythm on the human body cause various problems, research in this area is of great importance. On the other hand, concerning the COVID-19 pandemic, the fact that the vast majority of people work under artificial lighting shows that the problem is even more urgent. The aim of this work is to study the circadian efficiency of emission of general-purpose LED light sources.

2. DETERMINATION OF CIRCADIAN QUANTITIES

In recent years, much attention has been paid not only to the technical characteristics of LED lamps, such as energy-saving and color rendition quality (luminous efficiency and color rendition index) [11-13], but also to medical and biological aspects. The emission spectrum of LEDs differs from the emission spectra of other light sources. The spectrum of radiation wavelengths of the more widely used modern white LEDs covers an intense blue band with a maximum wavelength of about 450-460 nm and coincides with the maximum of the melatonin secretion attenuation spectrum. Currently, it is possible to study the biological effects of light without medical results based on known dependencies of the melatonin secretion attenuation spectrum (Figure 1) and relative spectral efficiency $V(\lambda)$ for daylight [6, 14, 15]. A simplified method was used to calculate the biological equivalent of LED radiation. The attenuation of melatonin secretion under the influence of light with different wavelengths can be determined using the circadian efficiency function $C(\lambda)$. With this function it is possible to calculate the circadian energy characteristic (X_{ec}) [3]:

$$X_{ec} = K\int X_{e\lambda}C(\lambda)d\lambda \quad (1)$$

The ratio of the integrals of the circadian and photometric characteristics is called the coefficient of circadian efficiency:

$$a_c = \frac{\int X_{e\lambda}C(\lambda)d\lambda}{\int X_{e\lambda}V(\lambda)d\lambda} \quad (2)$$

This ratio allows the comparison of the circadian efficiencies of different colors of light. To estimate the coefficient of circadian efficiency (calculated using a tricolor colorimeter or based on spectral data) by measuring color coordinates (x, y), a_c can be calculated from the following expression [3]:

$$a_c = \frac{1-x-y}{y} \quad (3)$$

The circadian efficiency coefficient a_c can be found from the graphical dependence with *CCT* shown in Figure 3.

The problems associated with the biological aspects of light are not yet well understood. There is also another issue that needs to be addressed with LED lighting. This is a blue light retinal hazard problem. Numerous biological and medical data suggest that the phototoxic effects of blue light are cumulative and lead to further, irreversible visual impairment. In [16], the molecular mechanisms of the negative effect of blue light on the retina were studied.

It shows that the action of blue light is a slow photochemical reaction, the results of which gradually accumulate throughout life. One of the causes of the disorder is lipofuscin, a phototoxic pigment that, through the selective absorption of light in the 440-460 nm band, requires free radicals that poison the retinal pigment epithelium.

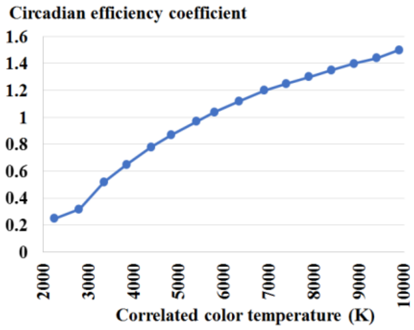

Figure 3. Dependence of the coefficient of circadian efficiency on the correlated color temperature [4]

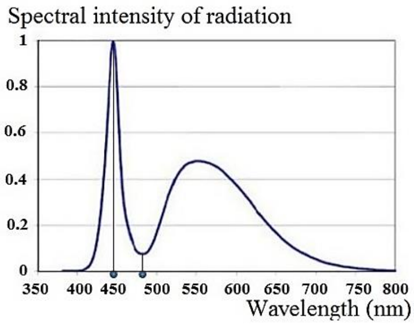

Figure 4. Emission spectrum of LED lamps [15]

The designs of the most common LEDs that are used to manufacture lamps and luminaires have a maximum emission in this dangerous region of the spectrum (Figure 4), so lamps and luminaires with a high *CCT* can increase the number of diseases of the retina. The transparency of the lenses in children is significantly higher than in adults, and the increased amount of blue light generated by high *CCT* in LEDs creates an additional dose of irradiance to the retina.

It should be noted that the blue light exposure dose is affected not by the height of the blue peak itself, but by the area under it and the ratio of this area to the area under the entire spectrum. The issue of blue light hazard is more about the brightness of sources, more precisely the energy brightness, weighted behind the function of dangerous blue light [15].

3. THE RESEARCH METHOD AND DISCUSSION OF THE MAIN MATERIAL

The studies compared the biological effects of LED lamps with *CCT* of 2680 to 6300 K, halogen incandescent lamps with *CCT* of 2800 K, and compact LL radiation with *CCT* of 2700 K and 4200 K. The calculation of color coordinates is based on the measurement of the radiation spectrum using a HAAS-2000 spectroradiometer (integrating sphere of 1m) [6].

Based on the results of the calculations, a graph of the dependence of the relative biological equivalent on the *CCT* of LED lamps was built (Figure 5).

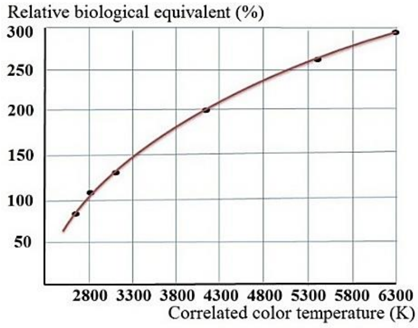

Figure 5. Relationship of relative biological equivalent to correlated color temperature

The graph shows that an increase in *CCT* leads to a decrease in the secretion of melatonin. The biological effect of LEDs is up to 300% higher than that of halogen incandescent lamps. Not only the circadian efficiency factor but also the duration of action (exposure) is important for the circadian effect of light on the human eye. A spectral band with the wavelength of 400-480 nm at 0.64 W/m^2 of irradiated energy for 3 hours leads to the destruction of retinal photoreceptor cells after 1-2 days [17]. It is known that exposure to cold white LEDs for an hour reduces the content of melatonin in the blood by 3-8%, but in this case, the level of radiation is not indicated [5].

The real danger of light in the violet-blue-mid-blue range of a high *CCT* LEDs is currently the subject of debate and biomedical research. Although the effect of modern LEDs on the human body has not been fully studied, numerous studies have shown that white LEDs have a special effect on circadian rhythms and sleep patterns.

Table 1. The relative effect of the spectrum of light sources with different color parameters on the attenuation of melatonin secretion

Lamp type	Correlated color temperature, K	Color coordinates		Circadian efficiency coefficient	Relative biological equivalent %
		x	*y*		
Incandescent halogen lamps	2800	0.4485	0.4020	0.35	100
LED lamps	2680	0.4633	0.414	0.2963	85
	2800	0.4486	0.4019	0.3719	105
	3100	0.4264	0.3931	0.4591	129
	4200	0.3714	0.3678	0.709	200
	5400	0.3347	0.3499	0.9014	257
	6300	0.3159	0.3385	1.0209	290
Compact luminescent lamps	2700	0.4646	0.4187	0.279	80
	4200	0.3731	0.375	0.6717	192

Although the control of daylight parameters is proposed by using automatic control systems depending on the requirements and environmental conditions (an automated lighting system with a changing color temperature depending on the time of day) [9], this method complicates lighting system and increases its cost.

It is recommended to refrain from using LEDs with *CCT* higher than 3500 K for lighting in children's and school institutions until generally accepted medical reports are received. To create a light environment close to natural light it is necessary to change the color of light during the day: warmer tones should be used in the morning and the evening (2700-3000 K), and during the day in rooms without natural light or in case it is insufficient lamps with *CCT* of 3500-5000 K must be used.

4. RESULTS

1) The spectral composition of artificial light sources is one of the important parameters and affects both visual function and human health. Biological activity of LED lamps with *CCT* higher than 6000 K exceeds the biological activity of halogen incandescent lamps by more than 3 times;
2) When developing light source standards, lighting standards, and their quality assessment, it is necessary to take into account parameters that affect human well-being and health;
3) In homes, children, and school institutions, it is advisable to use LED lamps whose biological effect does not exceed the biological effect of halogen incandescent lamps. This is explained by the fact that for more than 100 years of use of incandescent lamps, no negative effects on human physical and psychological health have been identified;
4) For household LED lamps it is required to limit *CCT* ($CCT \leq$ 3500 K). Lamps with $CCT >$ 3500 K can be offered for lighting industrial enterprises, public organizations, offices, retail facilities;
5) Introduce requirements for the emission spectrum of general-purpose LED lamps, including for lamps that will be used in everyday life, children's, schools, educational institutions, medical institutions, where emission spectra are of extreme significance.

NOMENCLATURES

1. Acronyms

LED: Light-Emitting Diode
LL: Luminescent Lamps

2. Symbols / Parameters

CCT: Correlated Color Temperatures
R^2: The coefficient correlation
λ_{max} : The maximal wavelength
$V(\lambda)$ *:* The relatively spectral efficiency
X_{ec} : The circadian energy characteristic
K : The coefficient equal per unit
$X_{e\lambda}$: The photometrical energy characteristic
$C(\lambda)$: The circadian efficiency functions
x , y *:* The color coordinates

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BIOGRAPHIES

Sabir Aghabaghir Baghirov was born in Azerbaijan, 1961. In 1978, he entered Kharkov Civil Engineering Institute, Ukraine. In 1983-1987, he continued his career at the Baku Electric Lamps Plant, Azerbaijan. In 1987, he entered Kharkov Civil Engineering Institute for a full-time postgraduate program on the specialty of lighting engineering and light sources. During his postgraduate studies, he worked as a junior researcher in the Scientific Research Sector of the Institute. In 1990, he successfully completed his postgraduate studies and was appointed chief technologist at Baku Electric Lamps Plant. In 1993, he defended his dissertation on "The development and improvement of methods for dosing and mass determination of mercury in fluorescent lamps" at Kharkov Institute of Municipal Engineers, Ukraine and received the degree of Candidate of Technical Sciences. From 1993, he worked as a bureau chief, engineer-technologist of the 1st category in the technical department of the Baku Electric Lamps Plant. From 2013 to 2018, he worked as the head of teaching laboratory at Azerbaijan Technical University, Baku, Azerbaijan, and from 2016 to 2018 as the Deputy Dean for Educational Affairs of Faculty of Electrical Engineering and Energy at the same university. In 2018, he was elected as a senior lecturer at the mentioned department. He is currently working on his doctoral dissertation on "Improving safety and energy efficiency in lighting systems" in higher education and research institutions of Ukraine. During his scientific activities he is the author of 35 articles, 9 inventions, 5 patents, and 15 study textbooks.

Shalala Sabir Baghirova was born in 1998. In 2020, she graduated from the Faculty of Energy, Electrical Engineering and Automation, Azerbaijan Technical University, Baku, Azerbaijan with a bachelor's degree in electrical engineering. In 2020, she entered the master's degree in Energy Management at Azerbaijan Technical University. She continued his scientific research to save electricity in lighting equipment and improve the quality of lighting. She is a participant of national and international scientific conferences and the author of a number of articles.

Svitlana Hryhorivna Kyslytsia was born in Ukraine, 1970. In 1993, she graduated from the Kharkiv National University of Urban Economy, Ukraine with degree in electrical engineering. In 2001, she received the degree of Candidate of Technical Sciences from Kharkiv National University of Urban Economy, Ukraine. Since 2002, she has been an Associate Professor at Department of Automation and Electric Drive at Poltava National Polytechnic University named after Yuri Kondratyuk, Ukraine. Currently, she works at Department of Automation, Electronics and Telecommunications of the same university. She continues his research in the field of light engineering and energy-saving technologies of light sources, control systems in electric power.

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