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Metrological requirements for measurements of circadian radiation

Piotr JAKUBOWSKI*, Irena FRYC

Electrical Engineering Faculty, Bialystok University of Technology,
Wiejska 45d, 15-351 Bialystok, Poland

*Corresponding author: piotr.7akubowski@gmail.com

The article presents a definition of circadian radiation and its influence on human beings. Typical sources of this radiation have been discussed and compared. As the availability of devices designed for circadian radiation measurement is very limited, and their quality is rather poor, there is a need for the development of a new meter which would deliver precise data. The paper presents available methods of optical radiation measurement which can be used in a circadian radiation assessment. Advantages and disadvantages of presented methods have been discussed. A light path in typical measurement instruments has been analyzed, as well as the impact of each component on the final result (*i.e.* the influence of spatial correction, optical filters and detectors). Original results of authors' research have been presented and the concept for decreasing the measurement error has been proposed.

Keywords: circadian radiation, optical measurement, LED lighting.

1. Introduction

One of the first association with the word "light" is vision, because optical radiation in a visible range is extremely important for human beings. It delivers most of information about the surrounding world, and determines our decisions and behavior. The vision is caused by the reaction of cones and rods to the light. Both kinds of receptors are located on retina and they are able to transform electromagnetic radiation into usable information for our brain. Their sensitivity is limited to the range between 380 and 780 nm, and it is not equal in this scope. Sensitivity of the human eye has been described by the so-called $V(\lambda)$ curve (Fig. 1).

It was always obvious that light is also responsible for synchronization of our biological clock, however the mechanism was difficult to capture. In 2001 it was proved that there are third class receptors on the retina of the human eye [1, 2], the so-called ipRGC (intrinsically photosensitive retinal ganglion cells). They utilize melanopsin which is a different photopigment sensitive to light in the range 380–600 nm, with its maximum at about 480 nm (Fig. 1). Although it is still in a visible range, the stimula-

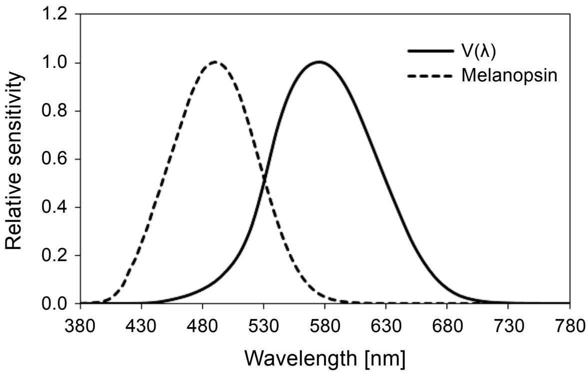

Fig. 1. Relative spectral sensitivity of $V(\lambda)$ and melanopsin [3].

tion of ipRGC is not generating any visual sensations, but activates the brain to control melatonin secretion. Finally, the melatonin concentration in the blood is responsible for the natural daily rhythm.

2. Circadian radiation

Circadian active radiation has a very big impact on our behavior. Besides of the control of the natural biological rhythm, it has an influence on the activity of the cerebral cortex and the quality of sleep. It may alleviate the effects of seasonal depression, help in the treatment of the alzheimer's disease and support the premature baby development. Nevertheless, the influence of circadian radiation on the human being is very complex and difficult to assess as it is not a function of just one parameter. The effect depends on irradiance, spatial distribution, time of a day and a year. It is individual and age -dependent, too. However, it has also been proved that the exposition may increase the risk of breast cancer [4].

As ipRGC stimulation can lead to positive and negative effects, it becomes a very interesting topic for researchers all over the world (leading institutes are: Lighting Research Center Rensselaer Polytechnic Institute, USA, or Helsinki University of Technology Centre for Metrology and Accreditation Metrology Research Institute). CIE (International Commission on Illumination) also recognizes this topic as very important and recommends further research on this radiation by positioning it as strategical. Moreover, CIE published a technical note TN003-2015 [5] which is a basic guide for researchers and gives the unified methods of assessment. It is recommended to use the most primal response of receptors, *i.e.* melanopsin sensitivity function and do not combine it with any additional effects on the human body (such as melatonin secretion). Another important recommendation is not to create new units of measurement but to use radiometric units with relevant comments about the used weight function (*i.e.* melanopic flux, melanopic irradiance).

Circadian radiation is also a very interesting area for lighting accessories manufactures as it gives new possibilities in luminaries and enable a creation an added value to their products. There are already first systems designed for schools or night shift workers which support alertness and concentration. Contemporarily, lighting regulations are related only to photometrical quantities [6], which are based on sensitivity of the human eye $V(\lambda)$. However, it might not be enough for full characterization of light as circadian active radiation can generate a big influence on the human body. Although the problem of circadian radiation becomes more and more important, there are still no regulations, limits and norms. Nevertheless, there is a concept to standardize this problem, and some preliminary ideas are reflected in DIN SPEC 5031-100 and DIN SPEC 67600:2013.

2.1. Sources of circadian active radiation

High efficiency light sources such as LEDs (light emitting diodes), fluorescent tubes, HID (high intensity discharge) lamps, OLEDs (organic light emitting diodes) have become very popular in lighting applications these days. Compared to traditional incandescent bulbs, new lamps have significant emission of electromagnetic radiation between 380 and 600 nm, which can be even 9 times higher than in case of tungsten bulbs (Figs. 2 and 3). As mentioned before, radiation in this range is responsible for synchronization of a natural biological clock of the human being (so-called circadian cycle).

The transformation from the traditional to LED-based lighting is very rapid today. A high efficiency is a key driver for this change. A deeper analysis of a wide variety of light sources available on the market [7, 8] shows that products with higher correlated color temperature (CCT) are more efficient and give better brightness perception in darkness (*i.e.* better scotopic to photopic vision factor S/P). However, they emit much more power in the range of circadian light. The effect is similar in case of HID lamps

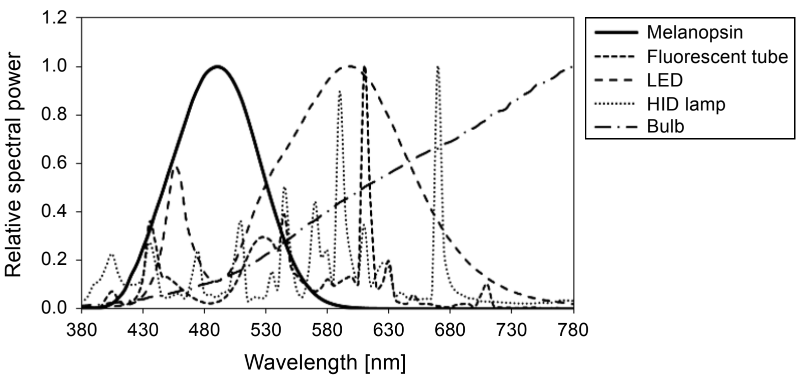

Fig. 2. Relative spectral power distributions of popular light sources and melanopsin spectral absorption distribution [3].

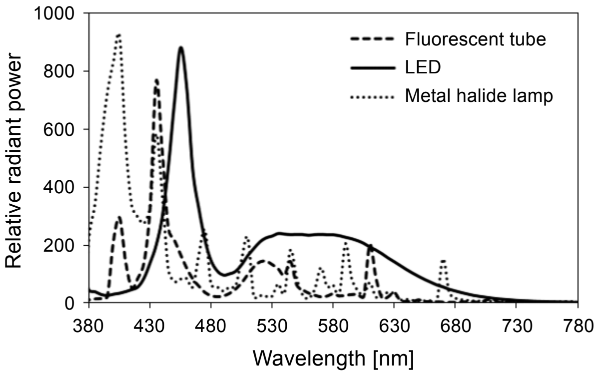

Fig. 3. Relative spectral radiant power distributions of a fluorescent tube, LED and metal halide lamp [3].

and OLEDs. Some rare exceptions can be observed in some specific products, but a general rule is still the same. Warm light (*i.e.* lower CCT) might be a partial solution. At a cost of lower efficiency and *S*/*P* factor, a lower emission of circadian radiation can be achieved. Nevertheless, it does not solve the problem. As it was mentioned before, circadian radiation has a very complex influence on the human body. It has been proved that lower doses of radiation and longtime exposition might have the same effect as high doses [4]. Any further studies on positive or negative effects of circadian radiation require a precise tool for proper assessment of the measured result.

3. Measurement of circadian radiation

3.1. Basic requirements for circadian meter

Circadian active radiation is just a part of visible spectrum, so all the standard measurement methods (devices) can be adopted for this purpose. However, the availability of devices designed for circadian radiation measurement is very limited (what may be caused by lack of appropriate regulations). There are some dosimeters available on the market, but their quality is rather poor [9]. They usually utilize a broadband detector, but their spectral sensitivity is not properly matched to the desired function. Proper spectral match by correction filters might improve their quality, but it is just a partial solution [10].

To deliver reliable results, the following basic requirements of this meter should be fulfilled:

1) Spectral correction – it is the starting point of any further considerations about a high quality meter, scientists consider few spectral curves today, but the most promising is the one proposed by CIE as it represents pure melanopsin sensitivity;

2) Spatial correction – phenomena of a circadian effect is the result of a superposition of flux from all the light sources in the given surrounding, so proper spatial sensitivity and meter head orientation should be considered;

3) Mobility – all the measurements should be proceeded *in situ* to consider all the environment conditions;

4) Easy to use and cost optimal – there is a chance that circadian light measurements become standardized one day, so the meter should be affordable, portable and intuitive (such as lux meter today).

3.2. Available measurement devices

A laboratory-class spectroradiometer is the most precise instrument which might be used for light measurement. Its monochromator enables a very narrow separation of wavelengths and discrimination of stray light. The result of measurement is given as a raw spectrum and all further operations are mathematically based, so the error is limited to numerical methods. Despite the strong advantages, it is not the best choice for circadian light measurement because it is a stationary device with rather long time measurement and requires a well-trained operator. In addition, a very high price will not make it popular in any measurements in the field.

A compact spectroradiometer seems to be an interesting alternative for a complex laboratory meter. Those kinds of devices become very popular today, as they enable to perform a wide variety of measurements. Those instruments are relatively inexpensive, pocket size and they can perform many operations on measured spectrum. However, their utility is limited because of a crosstalk between pixels and potentially high amount of stray light (level of 10^{-4}–10^{-3} per resolution unit). Because of the principle of its operation, this phenomenon is very difficult to eliminate [11]. The problem has a cumulative character and might influence the result in wide range of spectrum [12]. There are some methods of limiting this problem, but they are rather related to bigger stationary units.

A device with a broadband detector and spectral filter is the last kind of meter suitable for circadian measurement. The measurement in this device is performed on filtered light, by a photosensitive element. A functionality of such device is limited by it spectral characteristics, but it has a potential of delivering precise results (if quality of detector is high and filters have been properly designed). Compared to spectroradiometers, it has the simplest construction and small dimensions, so it can meet all basic requirements for newly designed optical radiation meters.

3.3. Designing principles for circadian radiation measurement device

A meter with a broadband detector and appropriate spectral filters seems to be an optimal solution for adaptation to circadian radiation measurement, thus all further considerations will be related to this device. The first step into the development of such unit is a deep understanding of phenomena along light path in a measurement head, which typically consists of three components: spatial correction element, spectral filter and detector.

Spatial correction element is the first on the light path. It has to deliver desired spatial sensitivity, which is usually a cosine function. The most common solution today is a specially designed diffusor which consists of transparent and highly diffuse glass, glued together. The authors performed measurements [3] of a few such elements, by

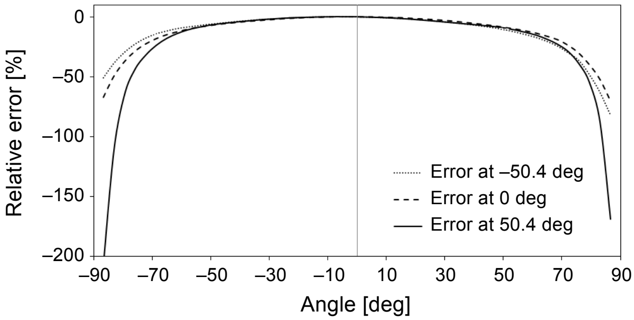

Fig. 4. Relative error to cosine function at different angles of light incidence on a diffusor.

illuminating them under different angles by a very narrow beam of white light. The results showed that diffusors do not reproduce precisely a cosine function, and the mismatch is getting higher for higher angles of incidence. The relative error reaches the level of about 15% for angles up to 60 deg, and then increases rapidly. Moreover, the relative error is nonsymmetrical (Fig. 4).

The next component after the spatial correction is a spectral correction filter with desired band-pass characteristics. But even if this filter is designed to have a perfect spectral match at normal light incidence (*i.e.* 0 degree), then this fact does not guarantee a low level of the spectral error for higher angles of incidence. Because of Fresnel losses and absorption in the filters, its spectral transmission characteristics might be suppressed and distorted (Fig. 5). In the result, the error caused by filters might be high and reach the level of tens of percents (Fig. 6).

The last light path component of this kind of a meter is a detector of optical radiation. Nowadays, a photodiode is the most common solution. High precision devices from the world class manufacturers can deliver high uniformity (0.1%) and very good time and temperature stability. Nevertheless, their spatial response might be a reason of errors. The sensitivity of photodiode S1337 from Hamamatsu has been measured for different angles of incidence and for a wide range of wavelength. The measurement was

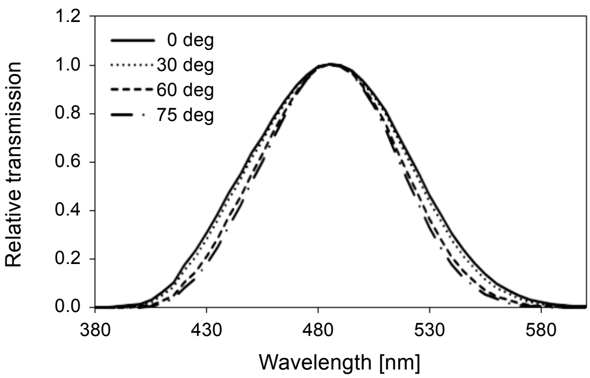

Fig. 5. Relative transmission of spectral filters at different angels of light incidence.

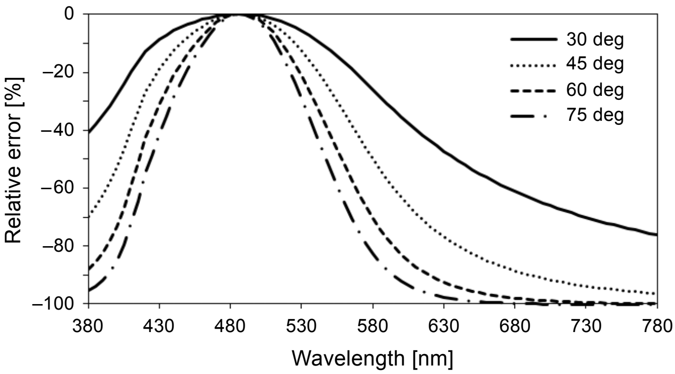

Fig. 6. Relative error caused by spectral filters at different angels of light incidence.

performed in a laboratory darkroom. Light was generated by 110 W halogen lamp and then splited in narrow bands by a monochromator. A lock-in amplifier synchronized with a chopper was used to reduce any background light. A measured detector was mounted on a rotary table and illuminated under several angles of incidence of light (Fig. 7). Results showed that higher angles of incidence lead to higher relative errors

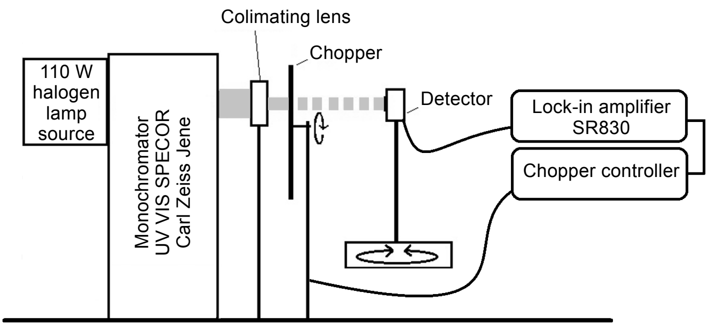

Fig. 7. Laboratory station for detectors measurements.

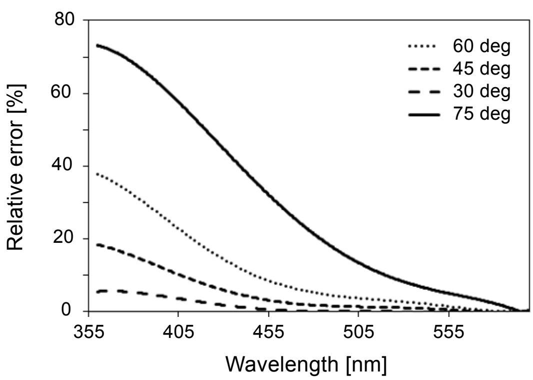

Fig. 8. Relative error of Hamamatsu S1337 photodiode at different angles of incidence.

when the signal is compared with that when light is falling under the normal (0 deg) angle of incidence. This phenomenon is increasing for shorter wavelengths (Fig. 8).

4. Conclusions

The research on circadian radiation becomes a very important field of human physiology today. Better understanding of this problem can lead to the improvement of life quality. Nevertheless, proper tools are required as the uncertainty may lead to wrong conclusions. To enable this, a new concept of the measurement head should be developed. If light is incident on spectral filters at the angle close to normal, it reaches a photodetector also on a very small angle. As a result, the total error of the meter can be limited.

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