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Review Article

Risks and Uncertainties in Photobiological Measurements

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Abstract

The risks and uncertainties in photobiological measurements have attracted more attention. Positive and negative effects of optical radiation on the visual analyzer, skin and psychophysiological functions of the human body have been established. Herein, standardized the quantities of optical radiation in 5 systems. Additionally, photobiological quantities and the traceability of their measurements were investigated. The risks and uncertainties of photobiological measurements were analyzed with the example of weighted radiance (L_B). Combining the influence of optical radiation on human body, the map of safety intervals was creatively proposed, and the connection between uncertainty and photobiological measurement has been established.

Keywords: Photobiological Risks; Photobiological Measurements; Optical Values; The Map of Safety Intervals; Traceability; Uncertainty

Introduction

Composed of ultraviolet, infrared and visible light, the optical radiation have both positive and negative effects on the human body and the environment. Photobiology is a discipline that studies the interaction between optical radiation and biological organs and tissues, and photobiological safety refers to the hazards of optical radiation to the human body [1]. With the development of artificial light sources, the quality of people's life has been improved, while people may be at greater risk of optical radiation. The International Commission for Non-Ionizing Radiation Protection (ICNIRP) provides different exposure safety limits for different types of exposure hazards based on the assessment of biophysical data. The International Commission of Illumination (CIE) and the International Electrotechnical Commission (IEC) also have different requirements for the measurement parameters and measurement wavelength ranges specified by different types of exposure hazards, and the measurement methods are complex. Due to the particularity and complexity of measurement in the field of photobiological safety, there is no unified photobiological safety measurement standard and corresponding value traceability system so far, so that photobiological safety measurement instruments cannot effectively trace the value of measurement results and the consistency is poor. Therefore, it is of great significance to carry out research on photobiological safety measurement standards and measurement methods, and to establish a measurement device and a traceability system for optical radiation exposure.

Classification of optical radiation and their effects on the human body

For various applications, there are three schemes for dividing the optical radiation spectrum into ranges shown in table 1 [1,2]. Physical No. 1 is widely used in science and technology for routine measurements, Physical No. 2 is used in astronomy, and Photobiological (CIE) is developed for health care.

Positive and negative effects of optical radiation on the visual analyzer, skin and psychophysiological functions of the human body have been established: on the one hand, certain doses of radiation are necessary for the normal functioning of the human body,

Physical No. 1	Physical No. 2	Photobiological (CIE)
Extreme UV (1-10 nm ~ 200 nm)	Vacuum UV (1-10 nm ~ 180 nm)	UV-C (100 nm ~ 280 nm)
Far UV (200 nm ~ 300 nm)	Medium UV (180 nm ~ 300 nm)	UV-B (280 nm ~ 315 nm)
Near UV (300 nm to 400 nm)	Near UVR (300 nm to 400 nm)	UV-A (315 nm ~ 360-400 nm)
Light (380 nm ~ 760 nm)	Light (400 nm ~ 700 nm)	light (360-400 nm ~ 760-780 nm)
Near IR (760 nm ~ 4000 nm)	Near IR (700 nm ~ 1200 nm)	IR-A (760-780 nm ~ 1400 nm)
Middle IR (4 μm ~ 14 μm)	Middle IR (1.2 um ~ 7 um)	IR-B (1.4 um ~ 3 um)
Far IR (14 μm ~ 100 μm)	Far IR (7 um ~ 1 mm)	IR-C (3 μm to 1 mm)
Submillimeter (100 μm ~ 1 mm)		

Table 1: Classification of optical radiation spectrum.

while on the other hand, there may be a danger of overexposure [3]. The positive effects of ultraviolet radiation include stimulation of basic biological processes, hemolysis and anti-rachitic action, removal of chemicals (manganese, mercury, lead) from the body and reduction of their toxic effects, improve body resistance, immunity to colds, resistance to cold, reduce fatigue and improve physical function. Favorable effects of optical radiation in the visible range - increasing human efficiency, stimulating the growth of humans, plants, microorganisms, fish and animals, restoring circadian rhythms, improving the functioning of the nervous system, increasing mindfulness, etc. Positive effects of infrared radiation - increasing metabolism, increasing room temperature. The effects of radiation can be general and local, and also differ in the duration of exposure.

UV-A sources - electric arc, oxy-fuel welding, plasma cutting and spraying, laser systems, gas discharge lamps, mercury-quartz lamps, mercury rectifiers; UV-B sources - ultraviolet fluorescent lamps, fluorescence of organic compounds. Negative effects - vitamin deficiency, disorders of phosphorus-calcium metabolism and bone formation, decrease in the protective properties of the body, excitation of fluorescence of organic compounds, headache, nausea, dizziness, increased fatigue and body temperature, nervous excitation, electrophthalmia, photophobia, corneal damage, influence on tissue proteins and lipids, dermatitis, fever, chills, hyperpigmentation and peeling, solar elastosis, development of keratosis, epidermal atrophy, changes in the gas composition of atmospheric air due to its ionization, the formation of ozone and nitrogen oxides. Sources of UV-C radiation - short-wave UV lamps (253.7 nm, 185 nm), UV lasers (126 nm), tunable vacuum ultraviolet sources (100-200 nm). Sources of visible radiation of the "blue" component (from 360 to 460 nm) - blue and green LEDs, video terminals, video walls. Negative effects: provoking oncological diseases during exposure at night, disruption of circadian rhythms, etc. Sources of visible radiation of the "red" component (from 600 to 780 nm) - side lights of cars, LEDs, retroreflectors. Negative effect: blinding. Sources of visible radiation of the "white" component - fluorescent lamps, etc. Negative effects: disruption of circadian rhythms, fatigue, flickering, stroboscopic effect. Sources of IR-A radiation - solid-state light-emitting diodes, semiconductor lasers. Negative effects - a decrease in the temperature of the lungs, brain, kidneys, etc., "sunstroke", headache, dizziness, increased heart rate and respiration, darkening in the eyes, impaired coordination of movements, loss of consciousness, eye disease, etc. IR sources - incandescent lamps. Negative effects: overflow of blood vessels, increased metabolism, decrease in the number of leukocytes and platelets, changes in the central nervous and cardiovascular systems (conjunctivitis, corneal clouding, retinal burns, etc. Sources of IR-C radiation - incandescent lamps. Negative effects: increased body surface temperature, tachycardia, etc.

The following systems of quantities have been standardized in order to describe optical radiation.

- Energy (radiometric) system - a system of energy quantities, which is used for measurements in the UV and IR ranges of optical radiation. It includes the following quantities: radiation energy (Q_e, J), radiation flux (Φ_e, W), radiant luminosity (M_e, $W \cdot m^{-2}$ sr^{-1}), irradiance (E_e, $W \cdot m^{-2}$);
- Light (photometric) system - photometric system of quantities is used for measurements in the visible range and includes: light energy (Q_v, lm s), luminous flux (Φ_v, lm), luminosity (M_v, lm m^{-2}), luminous intensity (I_v, cd), brightness (L_v, cd m^{-2}), illumination (E_v, lx = lm m^{-2});
- Photon system - the photon system is counted from the photon level and includes: photon energy (Q_p, J), photon number (N_p), photon flux (Φ_p), output photon radiation (M_p, C^{-1} m^{-2}), photon intensity (I_p), photon irradiance (E_p);

- Colorimetric system is a science and technology used to quantify and physically describe human perception of color [4]: color purity (p), brightness coefficients (L_R, L_G, L_B), brightness units (B_R, B_G, B_B), color coordinates (X, Y, Z).

Three SI units - candela, lumen, lux, are referred to as photobiological, since they contain physiological weight coefficients associated with the characteristics of human vision [5]. The photobiological system is used in the scientific study of beneficial and harmful interactions of light (technically non-ionizing radiation) in living organisms. It includes the following quantities: actinic dose (H_{act}, $J \cdot m^{-2}$), blue light hazard, light radiation efficiency (KB, v), blue light hazard, radiation efficiency (η_B); erythemal dose (H_{er}, $J\ m^{-2}$).

Since ionizing radiation transfers energy to the irradiated substance, the concept of absorbed dose D is used to describe such quantities - the ratio of the transferred energy to the mass. According to the decision of the CIPM in 2002, the value of the equivalent dose is the product of the absorbed dose D and the numerical coefficient Q, which takes into account the biological efficiency of radiation and depends on the energy and type of radiation [6]:

$$H = Q \cdot D \text{ --------- (1)}$$

For example, to calculate the erythemal irradiance, E_{er}, from an ultraviolet radiation source, which is obtained by weighting the spectral irradiance at a wavelength λ by the radiation efficiency at that wavelength causing erythema and summing over all wavelengths present in the source spectrum over the entire range wavelengths of the action spectrum [6]:

$$E_{er} = \int E_{\lambda}(\lambda) s_{er}(\lambda) d\lambda \text{ ---------- (2)}$$

Where $E_{\lambda}(\lambda)$ is the spectral intensity of radiation at a wavelength λ (usually indicated in the SI unit $W \cdot m^{-2} \cdot nm^{-1}$); $s_{er}(\lambda)$ is the spectral weighting function of erythema, expressed in the spectral radiometric system and normalized to 1 at its maximum spectral value.

The erythemal irradiance E_{er} thus determined goes back to the SI unit $W \cdot m^{-2}$. Photochemical and photobiological quantities can be determined using either a spectral-radiometric system or a spectral-photon system, which requires the use of certain weighting functions. Thus, by analogy with equation (2), erythema caused by a source of ultraviolet radiation can be characterized by the system of spectral distribution of photons using the radiation intensity of erythemal photons [6]:

$$E_{p,er} = \int E_{p,\lambda}(\lambda) s_{p,er}(\lambda) d\lambda \text{ ---------- (3)}$$

Where $E_{p,\lambda}(\lambda)$ is the spectral flux of photons per unit area at a wavelength λ (usually indicated in the unit of measurement $c^{-1} \cdot m^{-2} \cdot nm^{-1}$); $s_{p,er}(\lambda)$ is the spectral weighting function of erythema, expressed in the spectral photon distribution system and normalized to 1 at its maximum spectral value.

The intensity of emission of erythemal photons, $E_{p,er}$, determined in this way, is usually indicated in $s^{-1} \cdot m^{-2}$, since the number of photons is dimensionless. It follows from equations (2) and (3) that the relationship between the expressions for the spectrally weighted quantity in the two systems depends on both the spectral form $E_{\lambda}(\lambda)$ and the action spectrum. However, for the general response process A, the relationship between the forms of the two spectral weight functions $s_{p,A}(\lambda)$ and $s_{e,A}(\lambda)$ (in the photonic system and the radiometric system, respectively), which can be used to describe the effect, is determined [6]:

$$s_{p,A}(\lambda) = \gamma_A \cdot \frac{hc}{\lambda \cdot n_a(\lambda)} \cdot s_{e,A}(\lambda) \text{ ----------(4)}$$

Where γ_A is a constant (specified in units of J^{-1}), independent of the spectral illumination $E_{\lambda}(\lambda)$, which satisfies the requirement to set the maximum value $s_{p,A}(\lambda)$ to 1; h is Planck's constant; c is the speed of light in vacuum; $n_a(\lambda)$ is the refractive index in air at a given wavelength λ.

The relationship between systems can be illustrated in table 2 with the example of energy illumination.

Systems' names	Values' names	Формула
Energy	Energy illumination	$E_e = \frac{d\Phi_e}{dA}$ where Φ_e - radiant flux; A - area
Photometric	Illumination	$E_v = \frac{d\Phi_v}{dA}$ where Φ_v - light flux; A - area
Photon	Photon irradiance	$E_p = \frac{d\Phi_p}{dA}$ where Φ_p - photon flux; A - area
Photobiological	Spectral illumination	$E_\lambda = \frac{d\Phi_\lambda}{dAd\lambda}$ where Φ_λ- radiation power ratio; A - area; λ - wavelength

Table 2: Energy illumination in various systems of optical quantities.

Action spectra are defined in terms of the magnitude of the effect versus the wavelength. The radiation wavelength depends on the refractive index of the medium, which means that the value of the action spectrum at any given wavelength will vary depending on the medium for which that wavelength is defined. In general, the medium in question is air and the CIE action spectra mentioned above are applicable for wavelengths measured in air. The spectral weighting functions $s_{p,A}(\lambda)$ and $s_{e,A}(\lambda)$ describing the same effect are different in shape, and the peak wavelength of the effect is different when expressed in photon numbers or radiometric quantities.

Work by Júnia., et al. [7], in relation to studies of human growth hormone, taking into account the recommendations of ISO 17511: 2020, the concept of a reference system is proposed, including a reference standard sample, a reference method and a reference laboratory. The practical implementation of the system involves assigning a numerical value to a reference sample (for example, a human biological material) through its calibration by determining "real" values using a reference method (GC-MS) or measuring clinical samples by radioimmunoassay (cross-references provide commutability). However, the performance of the reference method "must be a fully definable written standard capable of measuring in absolute terms the analyte levels in clinical samples." The metrological traceability of human sample quantities according to ISO 17511:2020 extends to the highest available reference system component, ideally to RMP and Certified Reference Materials (CRM).

However, the ISO 17511: 2020 standard does not apply to properties indicated in the form of nominal and ordinal scales, where the value is not involved. According to study by Júnia., et al. [7], the assumption that, where possible, procedures that report SI units should be used to calibrate reference preparations may be erroneous. In the field of medical diagnostics and therapy, a class of units is also used to quantify the biological activity of certain substances, which cannot yet be expressed in SI units. This is due to the fact that the mechanism of the specific biological action of these substances has not yet been sufficiently studied to be measurable in terms of physicochemical parameters. In view of their importance to health and safety, the World Health Organization (WHO) has taken responsibility for defining the WHO International Units - WHO IU - for the biological activity of such substances.

To solve this problem, at the 24th meeting (September 19-20, 2019) of the BIPM Advisory Committee on Photometry and Radiometry, it was noted the need to involve other organizations in the field of lighting, chemistry and biology, in particular, the International Commission on Illumination (ICE), which published five functions of broadband sensitivity of human retinal photoreceptors (S, L, M, ipRGC and rods) of α-optical spectral efficiency $N_{\alpha}(\lambda)$ α-optical equivalent illumination: cyanoptic E_{sc}, chloropic E_{mc}, erythropoietin E_{lc}, melanopathic E_{z}, rhodopic E_{r} radiation [8]. Accordingly, photobiological units of these quantities are proposed - lux equivalents: 1) cyanoptic sc-lx, 2) chloropic mc-lx, 3) erythropoietin lc-lx, 4) melanopathic z-lx, 5) rhodopic r-lx, which are traceable to SI units by means of the invisible spectral efficiency coefficient $K_N \approx 73{,}000$ α-lm·W^{-1}.

Photobiological risks and approaches to their assessment

Risk is the impact of uncertainty on an object, which may have different aspects (for example, financial, health and safety, and environmental goals) [9]. Photobiological safety mainly includes 8 test items: photochemical ultraviolet hazard, small blue light source hazard, near ultraviolet eye hazard, infrared eye hazard, skin thermal hazard, retinal blue light hazard, retinal thermal hazard and retinal heat low hazard [10].

Take "Dangerous Dose of Blue Light Radiation to the Retina" as an example. To protect the retina from photochemical damage caused by prolonged exposure to blue light, the integral spectral radiance weighted with the blue light hazard function B (λ), i.e. the weighted radiance L_B, must not exceed the level defined as [10]:

$$L_B \cdot t = \sum_{300}^{700} \sum_{t} L_{\lambda}(\lambda, t) \cdot B(\lambda) \cdot \Delta t \Delta\lambda \le 10^6 \cdot J \cdot m^{-2} \cdot sr^{-1} \quad (t \le 10^4 s) \text{ --------(5)}$$

$$L_B = \sum_{300}^{700} \sum_{t} L_{\lambda} \cdot B(\lambda) \cdot \Delta\lambda \le 100 \cdot W \cdot m^{-2} \cdot sr^{-1} \quad (t > 10^4 s) \text{ ---------- (5.1)}$$

Where $L_{\lambda}(\lambda, t)$ - spectral irradiance, W·m^{-2}·sr^{-1}; B(λ) - spectral weight function of blue light hazard; Δλ - bandwidth, nm; t - exposure time, s.

For a weighted radiance L_B of a radiation source exceeding 100 W·m^{-2}·sr^{-1}, the maximum allowable exposure time tmax s is calculated by the formula:

$$t_{\max} = \frac{10^6}{L_B} \quad (\mathbf{t} \le 10^4 \mathbf{s}) \text{ ---------- (5.2)}$$

Where t_{max} is the permissible exposure time, s; L_B is the weighted radiance of blue light.

The weighted radiance L_B of the LED retinal blue light protection lamp can be directly measured with the photobiological safety

measurement system. The photobiological safety measurement system mainly consists of a standard light source, a spectroradiometer, a power supply system, and an electrical measurement system.

The experimental procedure is divided into four parts: illumination test, illumination test, illumination analysis and obtaining results. To ensure meter accuracy, a standard deuterium lamp and a luminous intensity reference lamp (standard illumination end) should be used to calibrate the irradiance sensor prior to experiment. After calibration, install a test lamp for testing. Finally, irradiance, luminance, and irradiance analysis results are calculated to obtain the final effective luminance LB that damages the retina with blue light.

Sources of measurement uncertainty in this test mainly include: (1) u_A - error caused by the repeatability of measurements on the LED lamp under test; (2) u_{B1} - measurement error caused by calibration error of a standard light source; (3) u_{B2} - measurement error caused by the spectroradiometer error; (4) u_{B3} - uncertainty caused by lamp power supply voltage; (5) u_{B4} - uncertainty caused by the mounting position of the lamp under test; (6) Uncertainty of u_{B5} due to environmental conditions.

Among them, the uncertainty of the reference lamp and the uncertainty of the spectroradiometer have a greater influence on the measurement uncertainty. Therefore, a high-precision spectroradiometer should be chosen in measurements as much as possible, and the reference lamp should be measured regularly to ensure the stability of the reference lamp.

Map of optical radiation safety intervals

In 2002, Berson and others [11] at Brown University discovered a third type of photoreceptor cell in mammalian retinal-retinal ganglion cells (ipRGCs). They found that they can transmit invisible light signals to the pineal gland of the hypothalamus. Participates in the regulation of the biological clock. The ipRGCs have special neural pathways to transmit light signals to the suprachiasmatic nucleus (SCN). The SCN is the brain's biological clock regulator, which transmits signals to the pineal body through neural pathways, thereby regulating the secretion of melatonin. Therefore, the effect of light on the human body is not only visual adaptation and perception, but also the effect of light on the circadian rhythm of the human body, including sleep, wakefulness cycle, body temperature rhythm, and hormone secretion rhythm.

The following table summarizes the effects of optical radiation on humans (skin, eyes, rhythm and psychology). Among them, the red means harmful, the green means beneficial, the yellow means it can be harmful or beneficial over time, and the gray means a lack of relevant data to make judgments.

	Wavelength (λ, nm)	Skin	Eyes	Rhythm	Psychology
UV-C	100-280				
UV-B	280-311				
	311-315				
UV-A	315-400				
White	Composite				
Violet	380-435				
Blue	435-500				
Cyan	500-520				
Green	520-565				
Yellow	565-590				
Orange	590-625				
Red	625-740				
IR-A	780-1400				
IR-B	1400-3000				
IR-C	3000 nm-1 mm				

Table 3: The map of safety intervals.

In other words, the red means risks, the green stands for safety, the yellow means uncertainty while the gray can also be regarded as uncertainty from the perspective of incomplete or imperfect definition of the measuring.

Conclusion

The photobiological quantities are standardized into 5 systems, namely: Energy (radiometric) system, Light (photometric) system, Photonic system, Colorimetric system and Photobiological system. Since photobiology is a developing subject, the map of safety intervals lacks relevant data support, it is necessary to further establish a complete optical radiation safety test and evaluation system with a unified photobiological safety measurement standard and corresponding numerical traceability system.

In assessing uncertainty, correlation issues are often artificially identified or deliberately ignored. This evaluation result carries certain risks for users and laboratories in evaluating the measurement uncertainty.

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