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ARTICLE

Blue Light Hazard: are exposure limit values protective enough for newborn infants?

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Abstract – Blue Light Hazard is an emerging concern for health of population. Nevertheless, acute exposure to blue rays from artificial light is well taken into account by normative requirements applicable to lamps engineering and risk for general population is low. There is also no evidence for a chronic effect of artificial lighting on retina for general population at radiance below exposure limit values. That said, children in the very first years of life constitute a specific population to consider. On one side, eye anatomy of very young infants is different from elder young people or adults. On the other side, infants can be in close contact with some luminous toys or night lights. This paper presents a first approach for taking into account the specific anatomy of newborn infants' eyes in blue light hazard evaluation. Results show that differences of crystalline lens transparency, focal length and pupil diameter could induce a significantly higher retinal exposure than for adult.

Keywords: artificial lighting / LED / blue light hazard / child / eye

1 Introduction

In 1976, Ham, Mueller and Sliney demonstrated the possibility of photochemical damage on the retina of rhesus monkeys under the action of high-intensity blue light applied during a relatively short exposure time (from few seconds to few hours) (Ham *et al.*, 1976). These damages, consecutive to acute exposure, are defined as class 2 (or Ham class) damages and are characterized by the destruction of photoreceptors and of the RPE (Retinal Pigmented Epithelium). In 1990, Van Norren and Schellekens showed (Van Norren and Schellekens, 1990) that rats were also subject to Ham class damages, that is why it is possible to study the biological mechanisms by experiments on rodents models. In a nutshell, Ham class damages are consecutive to non-thermic oxidative stress phenomena: blue light, focused on the highly irrigated (and therefore oxygenated) material constituting the retina, can lose its energy through the creation of ROS (Reactive Oxygen Species) which are particularly effective in causing the destruction of retinal cells by lipid peroxidation of their membranes. Many works have been carried out, even recently, to improve our understanding of the mechanisms of photochemical injury that remains quite poor (Iandiev *et al.*, 2008; Nakanishi-Ueda *et al.*, 2013; Shang *et al.*, 2014; Geiger *et al.*, 2015; Jaadane *et al.*, 2015; Chang *et al.*, 2016; Krigel *et al.*, 2016; Jaadane *et al.*, 2017; Shang *et al.*, 2017). In particular, it is not clearly known where ROS production takes place, although it seems that rhodopsin and lipofuscin play a role – perhaps the main – in their production (Youssef *et al.*, 2011).

Risk of Ham class damages is taken into account in the design of lamps and artificial lighting devices, thanks to current normative requirements (IEC, 2006). The Exposure Limit Values (ELV), proposed by the ICNIRP (International Commission for Non-Ionizing Radiation Protection) (ICNIRP, 2013), are widely accepted. For example, we confirmed in a previous article that in the field of general lighting there is no evidence that white phosphor coated LEDs are toxic for human at radiance below ELV (Point and Lambrozo, 2017). Nevertheless, ELV have been made by using an action spectrum adapted to adults and not to infants, as ICNIRP indicates. Moreover, biometry of child eye is different from biometry of adult eye, especially during the very first years of life. This paper proposes to take into account ocular parameter of newborns, extracted from relevant literature, to discuss the validity of current ELV for this specific population.

2 Method

2.1 Blue Light Hazard evaluation for adults: reminder

To evaluate and limit exposure to blue light, the ICNIRP has defined an action spectrum B(λ) and a maximum permissible dose to wavelengths covered by B(λ). The maximum permissible radiance dose D_b below which no health effect is expected is 10^6 J/(m^2.sr). In the photobiological safety standard IEC 62471: 2006, D_b is expressed as the

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product of blue light effective radiance L_b by the exposure time T (see Eq. (1)). (It must be noted that L_b has no sense for little punctual sources, *i.e.* whose size of emissive surface is lower than 2.2 mm. In such a case, relevant physical parameter would be blue light effective irradiance E_b).

$$D_b = L_b.T. \tag{1}$$

IEC 62471: 2006 describes a complete protocol for L_b evaluation of a single non-punctual source. L_b is expressed through equation (2).

$$L_b = \int_{300\text{nm}}^{700\text{nm}} L\lambda.B(\lambda).d\lambda \left(W/m^2/sr\right). \tag{2}$$

B(λ) is the mathematical function describing the blue light action spectrum, *i.e.* the efficacy with which some wavelengths can affect the retina. Lλ is the spectral radiance measured at 200 mm from light source on the FOV (Field of View) of the moving eye and therefore differs greatly from the conventional definition of radiance, as FOV may be greater than the apparent size of the source. The measurement of radiance on FOV reflects the willing to take into account eye movements, which increase angular distribution of light on the retina, reducing the retinal irradiance values. It is estimated that eye movements increase FOV size in proportion to the exposure duration following the empirical relationships presented in Table 1.

IEC 62471: 2006 defines also several risk groups depending on maximum exposure time. Limits for L_b values are made according to these exposure time values so that D_b stays below 10^6 J/(m^2.sr). The risk group increases as the time required to exceed D_b decreases (see Tab. 2).

The Table 2 must be read as follows:

- Exposed to a light source whose radiance is lower than 100 W/(m^2.sr), an observer can receive a radiance dose greater than 10^6 J/(m^2.sr) only for an exposure time longer than 10,000 s (about 2 hours and 45 minutes). This light source is classified in no risk group.
- Exposed to a light source whose radiance is higher than 100 W/(m^2.sr) but lower than 10,000 W/(m^2.sr), an observer can receive a radiance dose greater than 10^6 J/(m^2.sr) only for an exposure time over 100 s. This light source is classified in low risk group.
- Exposed to a light source whose radiance is higher than 10,000 W/(m^2.sr) but lower than 4,000,000 W/(m^2.sr), an observer can receive a radiance dose greater than 10^6 J/(m^2.sr) if the duration of exposure exceeds the timeline of eyelid reflex (0.25 second). Natural reflexes are here supposed to protect the retina of the observer. This light source is classified in medium risk group. This group is prohibited for light bulbs dedicated to domestic general lighting.
- Exposed to a light source whose radiance is higher than 4,000,000 W/(m^2.sr), the timeline of eyelid reflex is too long to prevent retinal damage. The maximum permissible radiance dose is exceeded “instantly”. This light source is classified in high risk group. This group is prohibited for light bulbs dedicated to domestic general lighting.

Table 1. FOV depending on observation duration.

	No risk group	Low risk group	Medium risk group	High risk group
T_{max} (s)	10,000	100	0.25	< 0.25
FOV (mrad)	100	11	1.7	1.7

Source: IEC 62471: 2006.

Table 2. Definition of risk groups depending on T and consequences on maximal L_b values.

	No risk group (RG0)	Low risk group (RG1)	Medium risk group (RG2)	High risk group (RG3)
T_{max} (s)	10,000	100	0.25	< 0.25
$L_{b\ max}$ (w/m^2/sr)	< 100	$< 10{,}000$	$< 4{,}000{,}000$	$> 4{,}000{,}000$

Source: IEC 62471-1: 2006.

As said, action spectrum B(λ) is not representative for young children whose lens is more transparent to short wavelengths. Moreover, child eye biometry is different from adult. However, calculation of retinal irradiance from source radiance varies with the squared focal length and pupil diameter as shown in equation (3) (Sliney, 1984). It means that, potentially, for a given light source, risk group could be significantly different for general population and for children, and especially for newborn infants whose eye differs most from the adult’s.

$$Er = \frac{\pi.L.t.d^2}{4f^2}, \tag{3}$$

with *Er* retinal irradiance, *t* the transmittance of ocular media, *d* the pupil size, *f* the focal length, and *L* the source radiance.

2.2 Blue Light Hazard evaluation for newborn infants: first approach

In order to determine if Exposure Limit Values recommended by the ICNIRP need to be revised especially for specific applications dedicated to newborns (for example, luminous toys or night lights), differences between adult and newborn infant eye anatomies must be investigated and introduced into ELV calculation. For this study, we reduce our study to examination:

- of the role of the action spectrum, as higher transparency of crystalline lens to short wavelengths can significantly modify irradiance values on retina;
- of the role of the eye focal length f and of the pupil diameter d on retinal exposure, because retinal irradiance, as seen on equation (3), is proportional to the square of d and inversely proportional to the square of *f*. *f* and *d* are the main variables for calculating the quantity of collected light by the eye.

2.2.1 Action spectrum

The transparency of the adult eye varies strongly according to the wavelengths of the incident light. High energy UV B or

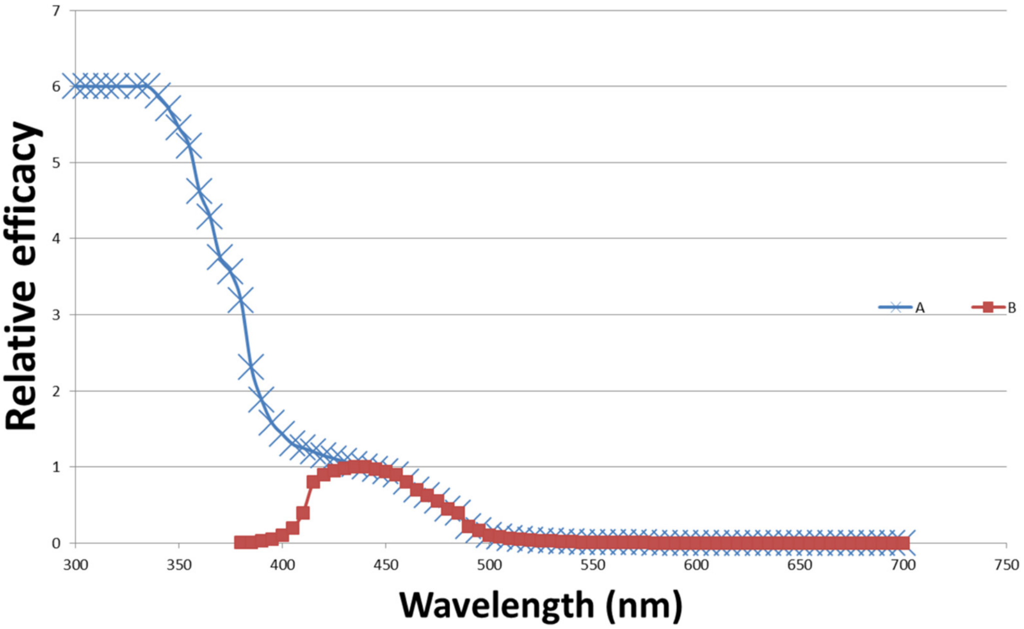

Fig. 1. Graphical view of A(λ) and B(λ).

UV C rays are absorbed by the cornea. At high dose, these UV rays can cause inflammation of the cornea (photokeratitis). The UV A rays, less energetic than the UV B or UV C rays, reach the crystalline lens which, under their action, can be affected by cataract. On the other side of the optical spectrum, the long IR rays are also stopped by the cornea. Short IR rays and visible rays can pass through the eye to the retina. At high dose, IR rays can cause thermal lesions. Visible light can cause thermal damages as well as Ham class damages.

For children, especially in the very first years of life, crystalline lens is more transparent to short wavelengths as violet light and UV A rays. As recommended by the ICNIRP, in the present study we apply for children the aphakic hazard function A(λ). Figure 1 shows the shape of A(λ), in comparison with B(λ).

2.2.2 Focal length

Child eye anatomy differs from adult eye anatomy. As reminded by Tan (Tan, 2009), newborn eye grows significantly during the first year of life. Then, eye still grows but more slightly. Lotmar (Lotmar, 1976) proposed a theoretical model for the eye of newborn infants, based on intra-ocular distances measurement made with ultrasonography and *in vitro* lens radii measurements. In this model, newborn infant focal length is found to be 15.74 mm. This value was chosen for calculation.

2.2.3 Pupil diameter

Roarty and Keltner (Roarty and Keltner, 1990) determined that pupil size of newborn infant is 3.8 ± 0.8 mm. This is in coherence with result from Higuchi (Higuchi *et al.*, 2014) who found a value close to 4 mm on elder children in bright condition. In this study, we chose the mean + 1 SD value from Roarty and Keltner, *i.e.* 4.6 mm, representing a maximal, protective value for pupil diameter.

3 Results

3.1 Effect of eye biometry on L_{bmax}

A light source is classified in no risk group (RG0) when an observer, placed at 20 cm from the source, can receive a radiance dose greater than 10^6 J/(m^2.sr) only for an exposure time longer than 10,000 s (about 2 hours and 45 minutes). It does concern light sources whose blue light effective radiance L_b is < 100 W/(m^2.sr). This corresponds to a maximal retinal radiant exposure of 2.2 J/cm^2 (for a Gullstrand eye model with a focal length of 17 mm, a pupil size of 3 mm and a transmittance of 0.9).

Taking into account the optical biometry of newborn infant as defined previously, we can calculate the radiance able to produce a radiant exposure of 2.2 J/cm^2 on newborn infant retina. The comparison with ELV (expressed in radiance) will permit to discuss their relevance.

The mathematical relationship we used to convert retinal exposure in radiance is equation (3).

For newborns, as explained, we choose $d = 4.6$ mm (pupil diameter), $f = 15.74$ mm (eye focal). Eye visible radiation transmittance t is chosen equal to 0.9.

With these parameter values, we find a new blue light effective radiance limit for newborns ($L_{bmax/newborn}$):

$$L_{b\ max/newborn} = 36\,\mathrm{W}/(\mathrm{m}^2.\mathrm{sr}).$$

This value is 2.8 times lower than current limit based on adult eye model (100 W/(m^2.sr)). Nevertheless, as explained previously, for a given light source, not B-weighted radiance but A-weighted radiance must be compared to this newborn blue light effective radiance limit.

3.2 Effect of A(λ) on measured value of L_b

A source must be compared to ELV after having been weighted by *ad hoc* action spectrum. For infants, aphakic

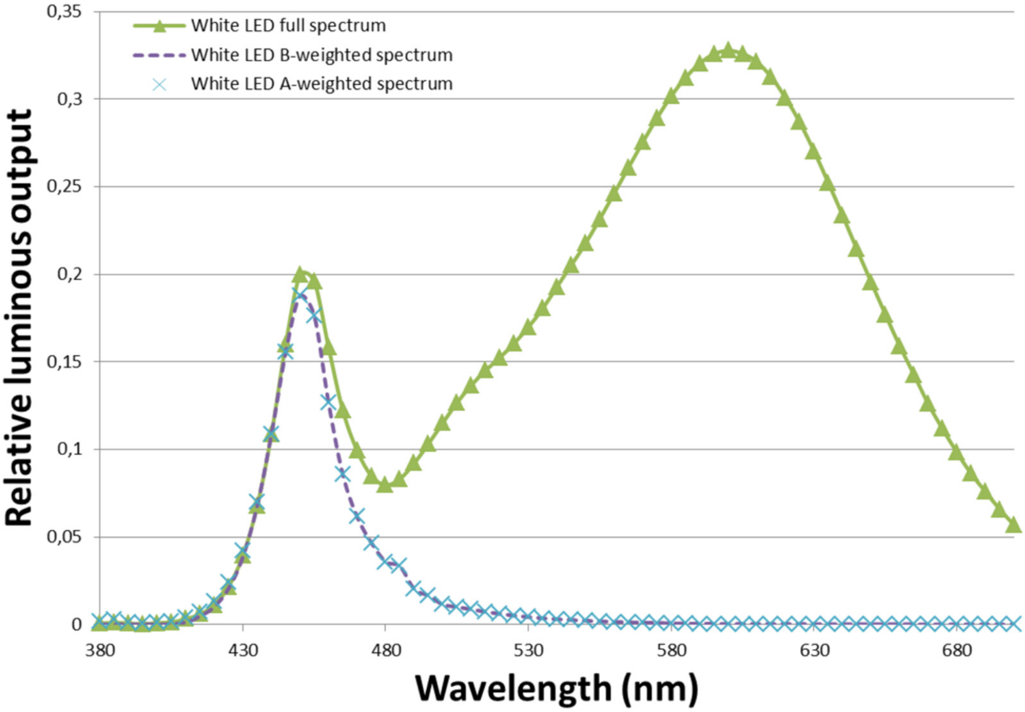

Fig. 2. Comparison of a 3200 K white LED full spectrum with its A-weighted spectrum and B-weighted spectrum.

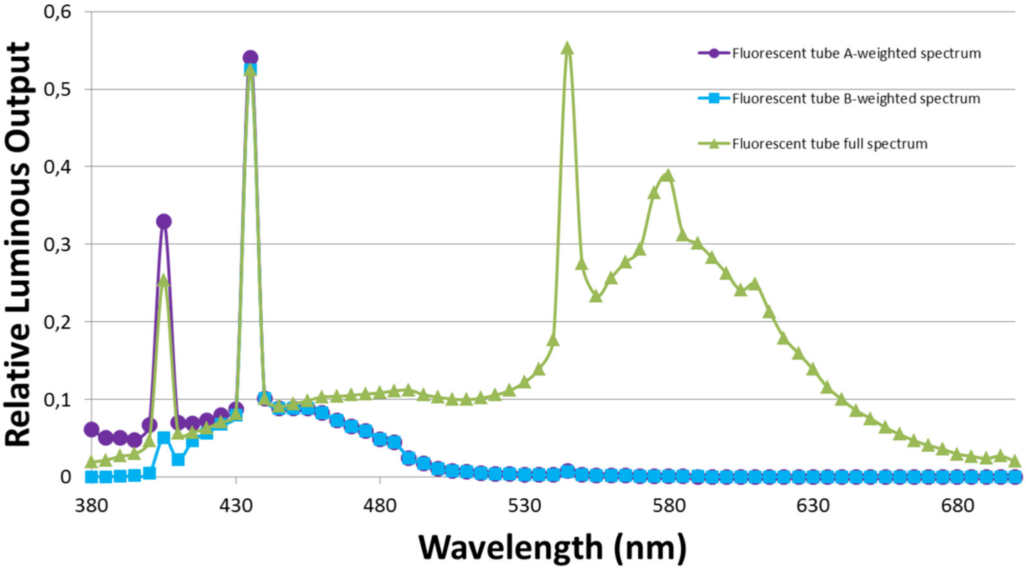

Fig. 3. Comparison of a 4000 K fluorescent tube full spectrum with its A-weighted spectrum and B-weighted spectrum.

action spectrum A(λ) is recommended. We have compared the relative increasing of L_b when full spectrum is weighted by A (λ) or B(λ) for three types of lamp technologies.

Figure 2 shows the spectrum of a typical 3200 K white phosphor coated LED analysed in one of our former study (Point and Lambrozo, 2017) and the same spectrum after weighting by B(λ) and A(λ). Proportion of B-weighted luminous output in ratio of full luminous output is 13%. Proportion of A-weighted luminous output in ratio of full luminous output is also 13%. For this LED, the use of A does not introduce a major change in retinal irradiance calculation. This comes from the fact that A and B are identical or very similar on the spectrum range of LED emission.

Figure 3 shows the spectrum of a 4000 K fluorescent tube and the same spectrum after weighting by B(λ) and A(λ). Proportion of B-weighted luminous output in ratio of full luminous output is 18%. Proportion of A-weighted luminous output in ratio of full luminous output is 25%. For this fluorescent tube, the use of A instead of B increases measured L_b by a factor close to 1.4.

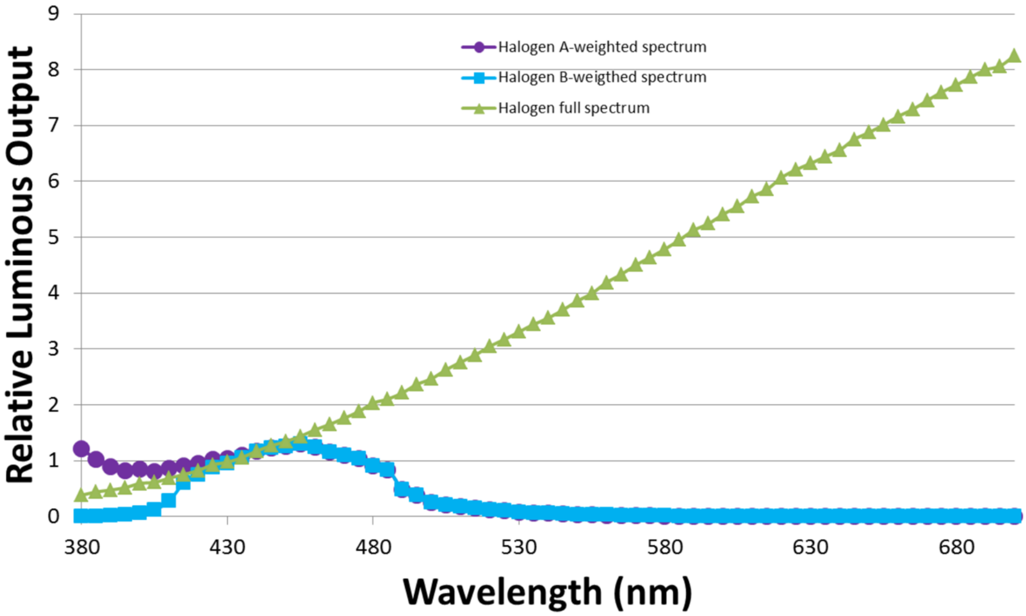

Fig. 4. Comparison of an halogen bulb full spectrum with its A-weighted spectrum and B-weighted spectrum.

Figure 4 shows the spectrum of an Halogen incandescent lamp and the same spectrum after weighting by B(λ) and A(λ). Proportion of B-weighted luminous output in ratio of full luminous output is 7%. Proportion of A-weighted luminous output in ratio of full luminous output is 10%. For this lamp, the use of A instead of B increases measured L_b by a factor close to 1.35.

4 Discussion

4.1 On A(λ)

For a given lamp, the use of A(λ) instead of B(λ) for children as recommended by the ICNIRP can increase the blue effective radiance depending on spectrum shape of the light source on short-wavelengths side.

For LED tested in this study, this increase is not observed. Taking into account that white phosphor coated LEDs working with a blue emitting chip are not designed for emitting violet and ultraviolet, and that a typical white phosphor coated LED has a nominal wavelengths ranging from 440 nm to 480 nm and a FWHM typically around 30 nm (Aubé *et al.*, 2013), we do not expect that the use of A(λ) instead of B(λ) increases significantly the evaluation of L_b for a white phosphor coated LED or even a blue LED. Nevertheless, it must be kept in mind that transparent crystalline lens of infants permits short-wavelengths to reach the retina. Consequently, a cumulative effect of blue light from LED with violet and UV-A from luminous environment cannot be excluded and should be investigated. Daylight LED technology, in which a violet component is added to the spectrum to better reproduce natural light, is today under technical investigation by manufacturers and must also draw attention: evaluation of such LEDs will have to be done using A(λ) instead of B(λ), to avoid underestimating biological effects on child eye retina.

For fluorescent tube tested in this study, this increase is significant (measured L_b increased by a factor 1.4), especially because of a strong spectral line of Hg at 404.6 nm. In a first approach, the use of A(λ) instead of B(λ) can increase the value of measured L_b when light source is a Hg-fluorescent tube.

For Halogen incandescent lamp tested in this study, the increase is also significant (measured L_b increased by a factor 1.35). In a first approach, the use of A(λ) instead of B(λ) can increase the value of measured L_b for Halogen incandescent lamps.

4.2 On newborn infant biometry

The biometry of newborn infant eye introduces some significant shift on how luminous energy is deposited on retina. While a 2.2 J/cm^2 radiant exposure is produced for adult by a source having an effective blue radiance of 100 W/(m^2.sr) (limit from RG0 to RG1), such a radiant exposure can be produced, according to our first approach, on newborn infant retina by a source having an effective blue radiance of 36 W/(m^2.sr), *i.e.* which is classified in no risk group (RG0). This result must be taken together with some concerns regarding retinal light absorption by infants: Guo and Tan (Guo and Tan, 2015) have simulated light absorption of infants retina, in function of ocular fundus sizes, wavelengths, and pigments concentrations by Monte Carlo method. They come to the conclusion that light absorption per volume could be at least two times higher than adults. As a consequence, the maximal retinal radiant exposure for newborn infants could be lower than 2.2 J/cm^2 and, consequently, limit for L_b still lower than 36 W/(m^2.sr).

These elements must draw attention especially on luminous toys and night lights to which newborns could have access in close proximity, for example in cradle. This kind of exposure could occur several times per day, potentially without any exposure time and distance control.

5 Conclusion

Our work confirms that child eye collects more light than adult eye does. Because of focal length and pupil diameter differences, limit for effective blue radiance for newborn infants could be around 2.8 times lower than for adult. Recommended action spectrum A(λ) seems not to bring some significant modification on measured L_b in the case of blue or white phosphor coated LED exposure in comparison with B (λ). The use of A(λ) seems nevertheless relevant for evaluating effective blue radiance of Halogen lamps and fluorescent tubes, which emit shorter wavelengths than do white or blue LEDs. Nevertheless, the higher transparency of newborn crystalline lens could allow some blue and violet/UV-A additive phenomena that remain to explore.

As newborn infants limit for L_b seems to be 2.8 lower than for adult, an RG0 lamps at the upper limit of the group, placed at 20 cm from infant eyes, could generate a retinal overexposure after 1 hour, as compared to 2 h 45 min for adult. Thus, according to our approach, RG0 could be not protective enough for lamps or light sources used in the close and direct environment of a newborn infant, for example luminous toys and night lights. Further research is required to analyse this issue in more depth. In the meantime, manufacturers of luminous devices for newborn infants could avoid deep blue, prefer the use of warm white light and limit the radiance in white light to few hundreds of $W/(m^2.sr)$; parents should also be educated to take care with luminous environment of their young children, keeping in mind, however, that short-wavelengths light is necessary to child eyes growth and must naturally not be deleted from their visual environment (Downie, 2017; Torii *et al.*, 2017).

Conflict of interest

The author is employed by Cooper Sécurité SAS which is a lighting manufacturer.

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