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Original Article

Using Temperature of IR Sources for Assessing Photochemical and Aphakic Retinal Hazard

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Abstract

Introduction

Blue light is a part of the spectrum with the highest energy content, which can reach the retina. The damage that it can cause to the retina is called photochemical or blue-light retinal injury. For the retinal injury assessment of the photochemical and aphakic retinal hazards in the wavelength range of 300-700 nm, use of effective spectral radiance limits ($W.m^{-2}.sr^{-1}$) seems to be slightly perplexing for ophthalmologists. However, in this study, the temperature (^{O}C) that can emit the same effective spectral radiance limit was detected using a computer code; this method could help prevent blue-light retinal injury.

Materials and Methods

The limits proposed by International Commission on Non-Ionizing Radiation Protection for blue-light induced photochemical and aphakic eye hazards were expressed in terms of temperature by a computer code for 13 Planckian sources that produce the same radiance. The calculated temperature by the computer code, here known as threshold temperature, is the maximum source temperature that for a specified viewing distance and source diameter does not cause the exposure at the receptor position to exceed the exposure limit.

Results

In terms of threshold temperature, the exposure limits for aphakia or infant retinal injury are much lower than retinal photochemical damage. For light sources with more effective radiances, these differences reach 800 K.

Conclusion

This method allows evaluation of photochemical and aphakic retinal hazard only by comparing the calculated threshold temperature by a computer code with the temperature of the radiant source, which may be beneficial for hygienist and ophthalmic clinicians.

Keywords: Aphakic eye, Blue-light photochemical, Exposure limit, Effective spectral radiance, Threshold temperature

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1. Introduction

Visual perception occurs when light with a wavelength between 400 and 760 nm reaches the retina. The retinal vulnerability to light has long been recognized [1]. One type of retinopathy caused by infrared (IR) radiation is the photochemical or blue-light retinal injury. Blue light is a part of the spectrum with the highest energy content, which can reach the retina, and the chance to sustain this damage is called blue light hazard.

In general, photochemical means that due to the high energy content of the incoming light some chemical reactions take place in the retina [2]. Photochemical damage to the retina typically occurs after a long interval and is mainly due to short-wavelength visible light; it leads to destruction of membranes of the photoreceptor outer segments, and finally photoreceptor death.

The impact of the absorbed light energy largely depends on the rate of energy deposition, which is correlated with exposure duration. Blue-light photochemical damage has been widely studied. For instance, Sliney et al. presented a plot of blue-light hazard for lasers and other optical sources, as they can cause edema, white spots, decreased visual acuity, and blurred vision [3, 4]. Various light sources were evaluated for photochemical hazard including the arc welding, plasma cutting, molten steel, iron, and glass, the filament or envelope of incandescent lamps, and light-emitting diodes.

Former studies evaluated IR radiation in all ranges of industrial hygiene interest through approximating the spectrum of the radiation emitted from hot sources to a blackbody spectrum [5, 6]. In addition to the drawbacks to the measurement of IR radiation in specific wavelength ranges, the exposure limit formulas are convoluted even for many hygienists and physicians. To overcome these problems, Madjidi et al. proposed a method for a Planckian emitter to replace the effective spectral radiance or irradiance exposure limits by threshold temperature, to protect the retina, cornea, or lens, based on American Conference of Governmental Industrial Hygienists threshold limit values (ACGIH TLVs) or exposure limits proposed by International Commission on Non-Ionizing Radiation Protection (ICNIRP) [7, 8].

This is the first attempt to use threshold temperature instead of effective spectral radiance in the range of visible light from 300 nm (light UV, deep blue) to 700 nm (deep red) for assessing photochemical and aphakic hazards, based on the recommended ICNIRP exposure limits [9]. This method allows determination of the difference between exposure limits for photochemical and aphakic hazard and functions of light source temperature. To this end, the threshold temperatures for the light sources whose effective radiance was measured by Okuno et al. were calculated by the proposed method

2. Materials and Methods

2.1. Spectrally weighted radiance integration

The effective blue-light radiances, L_B and L_A (in W.m^{-2}.sr^{-1}), were obtained by the product of the spectral radiance of the source, $L_{(\lambda, T)}$ (W.m^{-2}.sr^{-1}.nm^{-1}), blue-light photochemical weighting function (B_λ), and aphakic hazard weighting function (A_λ) as below:

$$L_B = \sum_{300}^{700} L_{(\lambda,T)}\, B_\lambda\, \Delta\lambda \tag{1}$$

$$L_A = \sum_{300}^{700} L_{(\lambda,T)}\, A_\lambda\, \Delta\lambda \tag{2}$$

Or could be rewritten in the integral form:

$$L_B = \int_{300}^{700} L_{(\lambda,T)}\, B_\lambda\, \Delta\lambda \tag{3}$$

$$L_A = \int_{300}^{700} L_{(\lambda,T)}\, A_\lambda\, \Delta\lambda \tag{4}$$

Where

$$L(\lambda,T) = (\frac{2c^2 h}{\lambda^5})(e^{hc/k_B\lambda T} - 1)^{-1} \tag{5}$$

In Equation (5), k_B is Boltzmann's constant (1.380×10^{-28} J/K), h is Planck's constant (6.625×10^{-34} J s), c is the speed of light (3.0× 10^{8} m/s), and

λ is the wavelength (m). The values of $B(\lambda)$ and $A(\lambda)$ are presented in Table 1 as recommended by ICNIRP [9]. For solution of the integrals (3) and (4), these integrals must first be segmented into sub integrals, as according to Table 1, there are various values covering the region 300-700 nm in which the hazard functions *B(λ)* and *A(λ)* were recommended by ICNIRP. Thus, it is necessary to rewrite the values of *B(λ)* and *A(λ)* in the matrix form of *B(λ(i,j))* and *A(λ(i,j))* that is defined in Tables 2 and 3. Finally, Equations (3) and (4) can be rewritten in a series of integrals as below:

$$L_B = \sum_{i=1}^{N1=14} \sum_{j=1}^{N2} B(\lambda(i,j)) \int_{\lambda(j)}^{\lambda(j)+4} L_{(\lambda,T)}\, d\lambda \qquad (6)$$

$$L_A = \sum_{i=1}^{N1=28} \sum_{j=1}^{N2} A(\lambda(i,j)) \int_{\lambda(j)}^{\lambda(j)+4} L_{(\lambda,T)}\, d\lambda \qquad (7)$$

In Equations (6) and (7), N_1 denotes the number of different dissimilar values for $B_{(\lambda)}$ and $A_{(\lambda)}$, and N_2 is the number of 5 nm intervals covering the range of 300-700 nm. The details of summation and integral calculation for Equations (6) and (7) were provided by Madjidi et al. [7].

TABLE 1. Aphakic and Blue light hazard functions recommended by ICNIRP

λ(nm)	*A(λ)*	*B(λ)*	***λ(nm)***	*A(λ)*	*B(λ)*	***λ(nm)***	*A(λ)*	*B(λ)*
300	6.00	0.01	**400**	1.43	0.100	**500**	0.100	0.100
305	6.00	0.01	**405**	1.30	0.200	**505**	0.079	0.079
310	6.00	0.01	**410**	1.25	0.400	**510**	0.063	0.063
315	6.00	0.01	**415**	1.20	0.800	**515**	0.050	0.050
320	6.00	0.01	**420**	1.15	0.900	**520**	0.040	0.040
325	6.00	0.01	**425**	1.11	0.950	**525**	0.032	0.032
330	6.00	0.01	**430**	1.07	0.980	**530**	0.025	0.025
335	6.00	0.01	**435**	1.03	1.000	**535**	0.020	0.020
340	5.88	0.01	**440**	1.000	1.000	**540**	0.016	0.016
345	5.71	0.01	**445**	0.970	0.970	**545**	0.013	0.013
350	5.46	0.01	**450**	0.940	0.940	**550**	0.010	0.010
355	5.22	0.01	**455**	0.900	0.900	**555**	0.008	0.008
360	4.62	0.01	**460**	0.800	0.800	**560**	0.006	0.006
365	4.29	0.01	**465**	0.700	0.700	**565**	0.005	0.005
370	3.75	0.01	**470**	0.620	0.620	**570**	0.004	0.004
375	3.56	0.01	**475**	0.550	0.550	**575**	0.003	0.003
380	3.19	0.01	**480**	0.450	0.450	**580**	0.002	0.002
385	2.31	0.125	**485**	0.400	0.400	**585**	0.002	0.002
390	1.88	0.025	**490**	0.022	0.022	**590**	0.001	0.001
395	1.58	0.05	**495**	0.016	0.016	**595-700**	0.001	0.001

Table 2. Values of *B* (*λ(i,j)*) as a function of wavelength used in equation (6).

i j	1	2	3	---	10	---	14
1	0.01	0.0125	0.900	1.000	0.04	0.800	0.001
---	---	---	---	---	---	---	---
4	0.01	0.050	0.980	0.0	0.900	0.620	0.400
---	---	---	---	---	---	---	---
7	0.01	0.200	0.0	0.0	0.0	0.0	0.0

Table 2. Values of A (*λ(i,j)*) as a function of wavelength used in equation (7).

i j	1	2	---	10	---	27	28
1	6.00	5.88	1.000	3.19	0.800	0.002	0.001
---	---	---	---	---	---	---	---
4	6.00	1.58	0.0	0.900	0.620	0.0	0.0
---	---	---	---	---	---	---	---
7	6.00	0.200	0.0	0.0	0.0	0.0	0.0

2.2. Hazard criteria based on ICNIRP exposure limits

The ICNIRP exposure limits/ACGIH TLVs for protection of the retina from photochemical-induced injury and aphakia for apparent diameters greater than 0.011 rad [9, 10], according to Okuno et al., are as below [4]:

$$L_B \le 10^6\ J\,m^{-2}\,sr^{-1} \quad \text{for } 0.25 \le t \le 10{,}000 \text{ s}$$

$$L_A \le 10^6\ J\,m^{-2}\,sr^{-1} \quad \text{for } t \le 10{,}000 \text{ s}$$

Where t is exposure duration in seconds. To find the temperatures corresponding to the exposure limits of photochemical and aphakic injury in the range of 300-700 nm two FORTRAN computer codes were developed separately. In both computer codes, the ICNIRP recommended exposure limits, L_B and L_A, in Equations (6) and (7) were controlled by the temperature values in $L_{(\lambda,T)}$, here known as threshold temperatures. The apparent diameters of the source and exposure duration were used as inputs to calculate the temperature corresponding to the permissible L_B and L_A values that are here noted as threshold temperature.

The main objective of this study is evaluating the threshold temperatures for light sources, the effective spectral radiance of which was measured by Okuno et al. to evaluate risk assessment of photochemical retinal damage and aphakia [4].

3. Results

3.1. Assessment of the validity of the source modeling

First, it is essential to test the accuracy of the source modeling. The best method for this purpose is comparison of the results from the Equations (6) and (7) with similar measurements. For example, Okuno et al. evaluated various light sources for blue-light photochemical hazard [4]. All the measurements were conducted with a circular measuring field of 1/16° (1.1 mrad). The permissible exposure duration per day in that study was calculated in accordance with the standards of ACGIH, which is the same as the guidelines put forth by ICNIRP.

For assessing the validity of the computer code for predicting effective spectral radiance, considering exposure limits, the computer code was run separately for each source with considering its permissible exposure time as input data. After running the code, the calculated results showed good consistency with the measured data that were provided by Okuno et al. [4]. The measured and calculated radiance values are listed in Table 4 with the maximum relative error of approximately 1.98%.

3.2. Estimated threshold temperatures

Based on ICNIRP exposure limits for photochemical and aphakic injuries as well as infant aphakia, and considering the calculated effective radiances in Table 4, the threshold temperatures were computed by the computer code [9]; the results are exhibited in Figure 1.

Our results demonstrated that the light source temperature for occurrence of retinal injury for aphakic eyes is much lower than photochemical-induced retinal injury. For light sources with higher temperatures, these differences can reach 800 K.

Table 4. Comparison between the results of Okuno et al. and equation (5) for different light sources

Light source	Measured effective radiance ($W\ m^{-2}sr^{-1}$) (Okuno et al.)	Calculated effective radiance ($W\ m^{-2}sr^{-1}$) equation(7)	Permissible exposure duration (s)
Xenon arc lamp, 500W	1100000	1101733	0.91
Metal halide arc lamp, 150W	23700	23881	42
High-pressure mercury arc lamp, 400W	23400	23269	43
Halogen lamp 500W, type 1	7840	7731	130
Halogen lamp 500W, type 2	4150	4187	240
Halogen lamp, 85W, infrared reflective	3030	3041	330
Halogen lamp, 150W, infrared reflective	2550	2568	390
Incandescent lamp, 200W	2060	2051	490
Incandescent lamp, 100W	1920	1929	520
Incandescent lamp, 60W	1880	1896	530
Halogen lamp, 75W, infrared reflective	1400	1410	710
High-pressure sodium arc lamp, 360W	1120	1129	890
High-pressure mercury lamp, 400W	265	264	3800

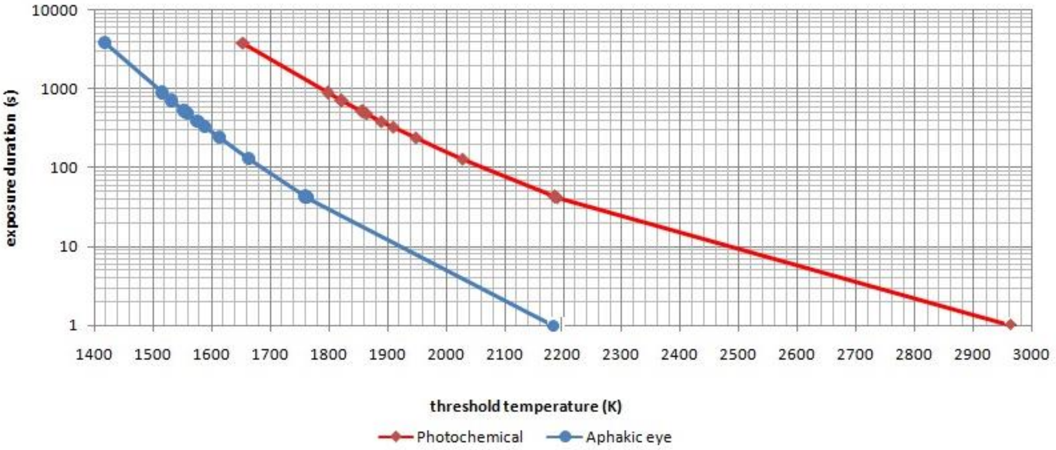

Figure 1. The threshold temperature for retinal photochemical and aphatic hazard plotted against permissible exposure duration, for light sources in table 4

4. Discussion

As mentioned before, it is possible to evaluate the blue-light exposure limits for Planckian emitters in range of 300-700 nm without any radiance measurement. This study described how temperature can substitute effective spectral radiance to evaluate photochemical and aphakic eye hazard exposure limit. The proposed method at first estimated the effective spectral radiances, and then estimated the threshold temperatures for the 13 cases based on ICNIRP exposure limits for photochemical and aphakic hazard.

It should be noted that all the light sources in Table 1 are supposed to be Plankian emitters. It seems that the ICNIRP exposure limits/ACGIH TLVs for aphakia are much lower than photochemical retinal damage, especially for light sources with more effective radiances.

5. Conclusion

The main objective of the present study was to propose a method to permit evaluation of retinal photochemical/aphakic hazard by comparing the threshold temperature with the temperature of the source. To this end, two computer codes were developed for aphakia and photochemical-induced retinal injury and were presented for 13 light sources in the wavelength range of 300-700 nm based on ICNIRP exposure limits. The results demonstrated that based on ICNIRP exposure limits/ACGIH TLVs for sources with apparent diameter of greater than 0.011 rad and exposure duration less of than 10,000 s, higher source temperatures lead to higher differences between threshold temperatures of photochemical and aphakic hazard.

It should be noted that the proposed method could only be used in cases where the source radiation could be well approximated to a blackbody source; thus, this could be a drawback to the widespread use of this method. However, the proposed method may be beneficial for prevention of ocular problems in those who are exposed to sever bright lights in their working environment.

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