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Light transmission through intraocular lenses with or without yellow chromophore (blue light filter) and its potential influence on functional vision in everyday environmental conditions

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In this research the factors used to evaluate the light transmission through two types of acrylic hydrophobic intraocular lenses, one that contained yellow chromophore that blocks blue light transmission and the other which did not contain that filter, were defined according to various light condition, e.g., daylight and at night. The potential influence of light transmission trough intraocular lenses with or without yellow chromophore on functional vision in everyday environmental conditions was analysed.

Keywords: light transmission; intraocular lenses; recognition of light sources

1. Introduction

The modification of spectral characteristics of optical radiation's transmission (including light) by different filters used to protect vision in ophthalmic optics as well as in artificial intraocular lenses (IOL) is common.[1,2] The spectral characteristics of protective filters is modified in order to block optical radiation at which levels of energy might harmfully influence the eye in the workplaces environment (e.g., laser technology, ultraviolet radiation, infrared radiation) or by light that may cause glare.[3] On the other hand, the modification of spectral characteristics of lenses used in spectacles is related mainly to the range of ultraviolet radiation and to lower the amount of light that reaches photoreceptors within the retina. To improve comfort of vision it is common to coat the surface of spectacles with photochromic filters, polarization filters that eliminate mirage effects, or interferential antireflection layers. Undoubtedly one of the biggest achievements of contemporary ophthalmic surgery of cloudy lens (cataract) was to create artificial IOL which allow users to achieve good postoperative visual acuity and adequate bio-compatibility.[4] Improvements in the field of IOL technology comprised searching for the best materials (hydrophobic acryl, hydrophilic acryl or silicon) on which the production of IOL is currently based as well as modification of shape and thickness that allowed surgeons to implant IOL through a very small opening in the eye. Premium IOLs, e.g., multifocal, accommodative and toric, help pseudophakic patients to be independent from spectacles, or fully corrected in the case of complicated refractive errors. From a technical point of view, changing of the light transmission by IOL is based on introducing pigment (chromophore) into the polymer structure of the IOL that limits light transmission in a defined spectral range.[5] The most often used IOL modification comprises introduction of yellow chromophore acting as a blue light filter. In the case of external eyeglasses, change of light transmission is short term and limited by the time wearing spectacles or protective masks. However, in subjects with implanted IOL the effect is permanent with potential influence on everyday light perception of the external environment as well as on the human circadian cycle.

Usually the luminous transmittance (light transmission factor) is defined according to the spectral visibility function of the average human eye for daylight/night vision,[6] spectral energy distribution of Standard Illuminant D65 or Illuminate A,[7] relative spectral distribution of signal lights [7] or spectral function for calculation of photobiological risk.[8] Considering these conditions, it is reasonable to assume that after cataract surgery with IOL implantation with yellow chromophore, the subject will perceive colours in a modified way as compare with pseudophakic patient without filter. As a consequence, IOL containing chromophore may influence the ability of coloured light recognition in everyday life and work environment, e.g., signal lights, colour pointers, displayers of the road traffic lights, indicator of dashboard, aircraft cockpit, etc., as well as the biological 'light stimulus' taking part in the mechanism whereby melatonin secretion is regulated.

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2. The method of calculating light transmission through IOL in various light conditions

The value of optical radiation transmission (including light), that crosses through any optical element, differs due to the way it is defined. The simplest way of defining transmission of optical radiation is to designate the proportion of the power of its stream falling on tested optical element to the stream that passes through this element. In fact the stream of optical radiation can be divided into many components of various wavelengths. The ratio of the streoptical radiation falling on the tested optical element to the stream that passed for any examined wavelength is defined as spectral transmittance, which is defined as follows:

$$\tau(\lambda) = \frac{\phi(\lambda)}{\phi_0(\lambda)}, \qquad (1)$$

where λ = wavelength in nanometres, $\phi_0(\lambda)$ = strength of stream falling on the optical element for wave length λ, $\phi(\lambda)$ = the strength of stream passing through the optical element for wave length λ.

Spectral transmittances at the function of wavelength is called as the spectral transmittance characteristics of an optical element. Spectral characteristic is the key element for calculation of the transmission of the optical radiation value.

The first stage in defining the equation which is going to be used to calculate transmission is to define the wave length range. In the case of defining optical radiation transmission (light) the range is from 380 to 780 nm. Another stage is based on choosing weight functions which are going to be considered at calculating transmission.[6] When these functions are not considered, the value of transmission is defined as mean spectral transmittance which is calculated by Equation (2):

$$\tau = \frac{\int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} \tau(\lambda) d\lambda}{N}, \qquad (2)$$

where λ = wavelength (nm), $\tau(\lambda)$ = spectral transmittance, N = integer corresponding to the value of measurement step at the measurement of spectral transmittance characteristics (e.g., for a measurement step 1 nm, in a range of wavelength of 380 to 780 nm, $N = (780 - 380) + 1 = 401$).

The value of optical radiation transmission might consider spectral energy distribution of any illuminants (e.g., Illuminant A for artificial light or D65 for natural light), as well as spectral visibility function of the average human eye for daylight or night vision distribution. Calculated in this way, the value of the light transmittance factor is defined by Equation (3):

$$\tau_v = \frac{\int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} \tau(\lambda) \cdot V(\lambda) \cdot S(\lambda) \cdot d\lambda}{\int_{380\,\mathrm{nm}}^{780\,\mathrm{nm}} V(\lambda) \cdot S(\lambda) \cdot d\lambda}, \qquad (3)$$

where λ = wavelength (nm), $\tau(\lambda)$ = spectral transmittance, $S(\lambda)$ = spectral energy distribution (e.g., D65 or A), $V(\lambda)$ = spectral visibility function of the average human eye for daylight or night vision distribution.

Because of differences in the spectral energy distribution and spectral visibility function of the average human eye for daylight or night vision distribution (Figures 1 and 2), the values of average spectral transmittance factor (Equation 2) and light transmittance factors (Equation 3) might differ significantly. This difference depends on the process of spectral transmittance characteristics itself.

The spectral characteristics of the light transmission might be also used for the calculation of factors that define ability for recognition of signal red (R), yellow (Y), green (G) and blue (B) light. The transmittance is weighted by spectral distribution of incandescent signal lights and the sensitivity of the human eye (τ_{signR}, τ_{signY}, τ_{signG}, τ_{signB})

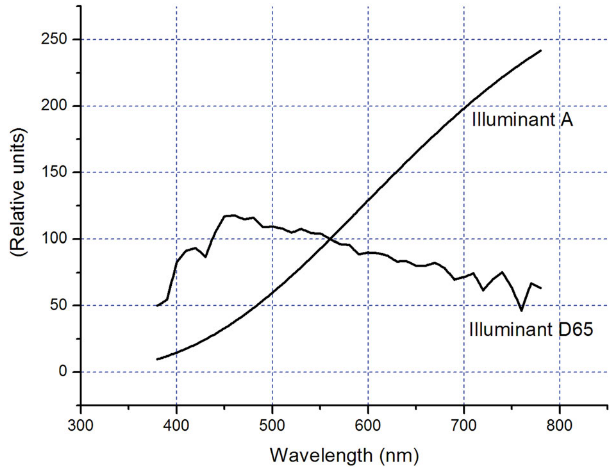

Figure 1. Spectral energy distribution for illuminant A and D65.[7]

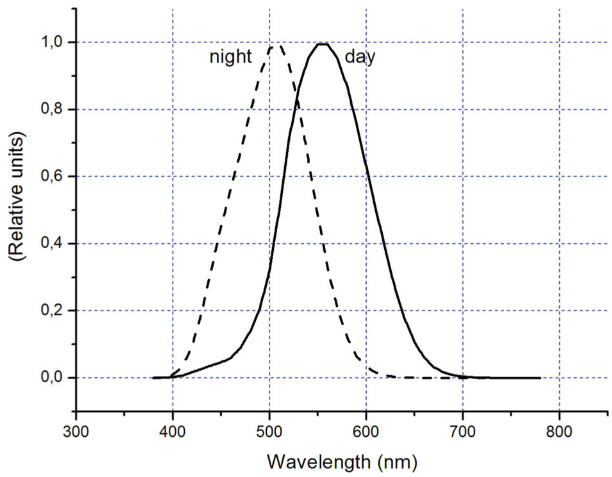

Figure 2. Spectral visibility function of the average human eye for daylight and night vision distribution.[6]

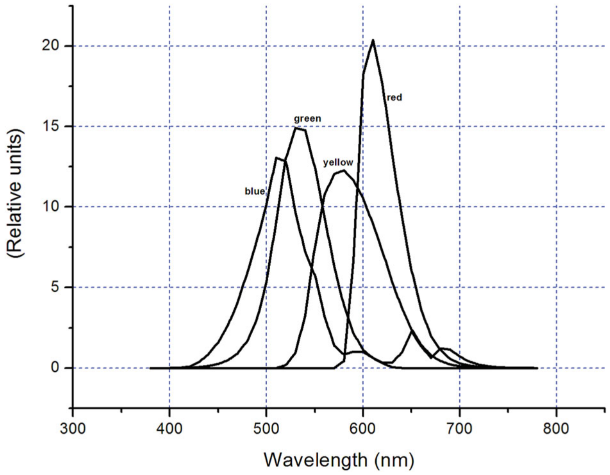

Figure 3. Spectral distribution of incandescent signal lights (for bulb light).[7]

and is calculated by Equation (4) [9]:

$$\tau_{\text{sign}} = \frac{\int_{380\text{ nm}}^{780\text{ nm}} \tau(\lambda) \cdot \tau_S(\lambda) \cdot V(\lambda) \cdot S_{A\lambda}(\lambda) \cdot d\lambda}{\int_{380\text{ nm}}^{780\text{ nm}} \tau_S(\lambda) \cdot V(\lambda) \cdot S_{A\lambda}(\lambda) \cdot d\lambda}, \quad (4)$$

where $S_{\text{A}\ \lambda}(\lambda)$ = spectral energy distribution of Standard Illuminant A (or 3200 K for blue signal light), $V(\lambda)$ = spectral visibility function of the average human eye for daylight vision, $\tau_{\text{S}}(\lambda)$ = spectral transmittance for traffic signal lens.

Spectral transmittance for signal lights depends on the type of light source. Different distributions are used in case of incandescent lights and LEDs. Sample spectral transmittance of signal light distributions for incandescent light sources are presented in Figure 3.

Transmittance factors including spectral distribution of signal lights are used to calculate relative visual attenuation quotient for signal light detection (Q_{sign}).[9] This quotient for signal red (R), yellow (Y), green (G) and blue (B) light (Q_{signR}, Q_{signY}, Q_{signG}, Q_{signB}) is calculated by Equation (5):

$$Q_{\text{sign}} = \frac{\tau_{\text{sign}}}{\tau_V}, \quad (5)$$

where τ_{sign} = spectral transmittance weighted by spectral distribution of incandescent signal lights and sensitivity of the human eye, τ_v = luminous transmittance (weighted by spectral visibility function of the average human eye for daylight and spectral energy distribution of Standard Illuminant D65).

3. Tested samples and research methods

The research consists of the comparison of light transmission for two types of hydrophobic acrylic IOL with the same refractive power of 20.0 dioptres, containing yellow chromophore (AcrySof® Natural Sn60AT Alcon Lab, USA) and without chromophore (Alcon Labs). The light transmission was evaluated, in daylight and in night conditions. The spectral characteristics were measured using the following factors:

- mean spectral transmittance (τ),
- luminous transmittance weighted by spectral energy distribution of Standard Illuminant D65 and spectral visibility function of the average human eye for daylight vision ($\tau_{v\text{A/day}}$),
- luminous transmittance weighted by spectral energy distribution of Standard Illuminant A and spectral visibility function of the average human eye for night vision ($\tau_{v\text{A/night}}$),
- luminous transmittance weighted by spectral energy distribution of Standard Illuminant D65 and spectral visibility function of the average human eye for daylight vision ($\tau_{v\text{D65/day}}$),
- luminous transmittance weighted by spectral energy distribution of Standard Illuminant D65 and spectral

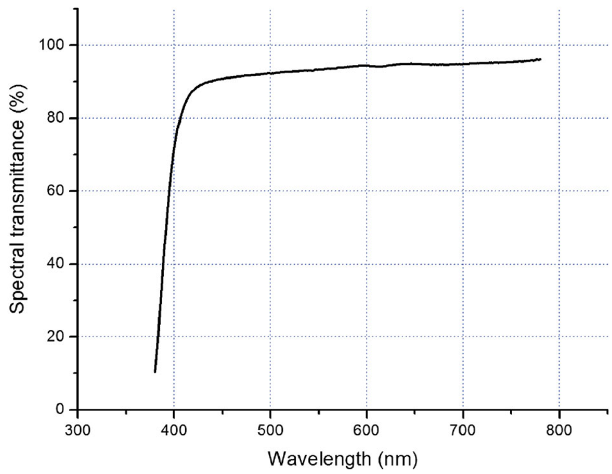

Figure 4. Spectral characteristics of intraocular lenses without chromophore light filter.

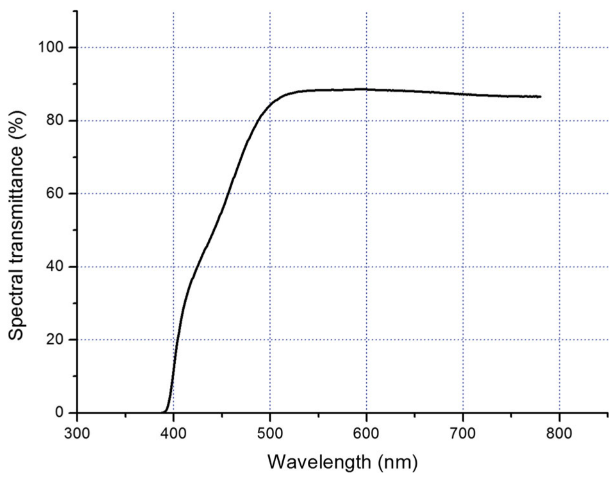

Figure 5. Spectral characteristic of intraocular lenses with chromophore light filter.

visibility function of the average human eye for night vision ($\tau_{v\mathrm{D65/night}}$),

- transmittance of signal lights (τ_{sign}),
- relative visual attenuation quotient for signal light detection (Q_{sign}).

Measurements were performed with the use of a two-beamed spectrophotometer CARY 5000 (Varian Inc., Australia) with the step of every 1 nm. Diagrams of measured spectral characteristics are shown in the Figures 4 and 5.

4. Results

Results of measured factors are presented in Tables 1–3.

Table 1. Light transmission factor.

Light transmission factor (%)	Type of IOL		The difference of factors for IOL without and with blue light chromophore
	Without chromophore	With chromophore	
τ	93.70	87.75	5.95
$\tau_{v\mathrm{A/day}}$	92.55	82.45	10.1
$\tau_{v\mathrm{A/night}}$	93.39	86.77	6.62
$\tau_{v\mathrm{D65/day}}$	92.14	78.41	13.73
$\tau_{v\mathrm{D65/night}}$	90.43	75.19	15.24
M	92.44	82.11	10.33
SD	1.298	5.367	3.706

Note: IOL = intraocular lenses; τ = mean spectral transmittance; τ_vA/day = luminous transmittance weighted by spectral energy distribution (Illuminant A) for daylight vision; τ_vA/night = luminous transmittance weighted by spectral energy distribution (Illuminant A) for night vision; τ_vD65/day = luminous transmittance weighted by spectral energy distribution (Illuminant D65) for daylight vision; τ_vD65/dnight = luminous transmittance weighted by spectral energy distribution (Illuminant D65) for night vision.

Table 2. Signal light transmission factor.

Signal light transmission factor (%)	Type of IOL		The difference of factors for IOL without and with blue light chromophore
	Without chromophore	With chromophore	
τ_{signR}	94.47	88.33	6.14
τ_{signY}	94.06	88.39	5.67
τ_{signG}	92.76	86.85	5.91
τ_{signB}	93.42	87.02	6.40
M	93.68	87.65	6.03
SD	0.75	0.83	0.27

Note: IOL = intraocular lenses; τ_{sign}R = transmittance of red signal lights; τ_{sign}Y = transmittance of yellow signal lights; τ_{sign}G = transmittance of green signal lights; τ_{sign}B = transmittance of blue signal lights.

Table 3. Relative visual attenuation quotient for signal light detection factor.

Relative visual attenuation quotient for signal light detection factor (%)	Type of IOL		The difference of factors for IOL without and with blue light chromophore
	Without chromophore	With chromophore	
Q_{signR}	1.01	1.01	0.00
Q_{signY}	1.01	1.02	– 0.01
Q_{signG}	1.00	0.99	0.01
Q_{signB}	0.99	0.96	0.03
M	1.00	0.995	0.005
SD	0.0096	0.0265	0.0148

Note: IOL = intraocular lenses; Q_{sign}R = relative visual attenuation quotient for red signal light detection; Q_{sign}Y = relative visual attenuation quotient for yellow signal light detection; Q_{sign}G = relative visual attenuation quotient for green signal light detection; Q_{sign}B = relative visual attenuation quotient for blue signal light detection.

5. Discussion and conclusions

Luminous transmittance weighted by spectral energy distribution of Standard Illuminant D65 and spectral visibility function of the average human eye for daylight vision ($\tau_{v\mathrm{D65/day}}$) is commonly used to characterize the amount of light that crosses through optical elements used in ophthalmic optics. There are no specified factors to characterize light transmission through the artificial IOL implanted during cataract surgery. Presented results show significantly lower value of light transmission (74.41% and 92.14%) for IOL containing blue light filter as compare to non-modified IOL, respectively. Values for light transmission that are specified by the manufacturer are in a narrow range of 95–99% and depends on the thickness (refractive power) of IOL. In practice, assessment of those factors is performed by the company using polymeric samples that are not connected with the production process. What is even more interesting, there is a significantly lower difference of 6% in the amount of light passing through the IOL with and without the blue light filter according to the mean spectral transmittance. Considering the obtained data one may assume that IOL with blue light filter has relatively good radiation transmission, which distribution is defined by A illuminant in night vision conditions. The values of luminous transmittance weighted by spectral energy distribution of Standard Illuminant A and spectral visibility function of the average human eye for night vision ($\tau_{v\mathrm{A/night}}$) for examined yellow chromophore and without chromophore IOL is 86.77% and 99.39%, respectively. The difference in amount of light that passes through non-modified IOL and IOL with chromophore is significantly lower in night conditions as compared to the daylight conditions. The obtained values of the light transmission factors of the two types of IOL show that there is higher transmission in the case of IOL without blue chromophore. On the other hand, it seems reasonable to suggest that blocking blue light radiation in twilight (mesopic) conditions potentially may improve the quality of vision. Here we considered the well known Purkinje phenomenon which describes the higher sensitivity of retinal photoreceptors during the night on shortwave radiation (blue light spectrum) in comparison to the spectrum of light with longer wave (e.g., red light). With this in mind the increased contrast as a result of diminished amount of blue light radiation can be expected. There were no differences between two types of IOL in term of the obtained values of signal light transmittance factors (Table 2), which for every type of signal light was 6%. Moreover the standard deviations for signal light transmittance for IOL without and with blue light filter were 0.75% and 0.83%, respectively. As a consequence there are no differences between values of relative visual attenuation quotient for signal light detection factors.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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