Determination of the action spectrum of the blue-light hazard for different intraocular lenses

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The spectral transmittance of various models of intraocular lenses (IOLs) has been studied. Significant differences among them were found, primarily regarding the cutoff wavelength. Based on these findings, modifications of the action spectrum for the blue-light hazard photobiological effect are proposed for each type of IOL. Moreover, the potential hazard of a representative range of radiation sources to subjects implanted with those IOLs has been calculated based on the corrected action spectra.

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1. INTRODUCTION

The human eye is exposed to damage through different mechanisms due to the optical radiation that it absorbs. Exposure to ultraviolet (UV) radiation and infrared (IR) radiation by the cornea or the crystalline lens can produce severe photochemical or thermal injuries, depending on the exposure duration and several other factors.[1] The retina, in its turn, can also suffer from thermal injury through absorption of high-intensity optical radiation. For lower values of the irradiance but for longer exposure times, the incident optical radiation can trigger photochemical reactions that convert chemically unstable molecules into one or more other molecule types. This causes photochemical injuries to the retina, known as blue-light photochemical retinal hazard (BLH) or photoretinitis.

The photobiological effect known as BLH is characterized by its action spectrum, which represents the relative weight of each wavelength in terms of the potential damage it can cause to the retina. This permits a direct comparison of different radiation sources to determine the relative effectiveness or the potential hazard of each. The original biological research relating to photoretinitis included the determination of the action spectra for this effect. Studies were performed by a number of scientists, but two series of fundamental studies were performed by a group at the Medical College of Virginia[2–6] and another at the University of Texas.[7] Their pioneering work provided the basis for threshold limit values (TLVs) and the BLH action spectrum recommended by the American Conference of Governmental Industrial Hygienists[8,9] and more recently by the International Commission on Non-Ionizing Radiation Protection.[10] The standard weighting function $B(\lambda)$ was first recommended by Sliney and Bitran.[9] They based this weighting function on the experimental results of Ham *et al.*,[2,3] which were obtained from research studies employing rhesus monkeys. Subsequently, this function was adopted by the American Conference of Governmental Industrial Hygienists, which used this function to establish a TLV for human exposure.

In addition to the function $B(\lambda)$ for the normal eye, an additional function $A(\lambda)$ was later developed based on studies of Ham and co-workers in rhesus monkeys with the crystalline lens surgically removed.[3] This was to simulate the viewing condition that could occur when a cataract patient having no lens (aphake) or an intraocular lens (IOL) without UV-A absorption, viewed an intense light source. The function $A(\lambda)$ (the aphake hazard function) should then be applied for persons whose crystalline lens has been removed through a surgical procedure or for those who do not have an IOL that absorbs UV radiant energy in the UV-A spectral region. Figure 1 shows the two different action spectra for BLH: $B(\lambda)$, which represents the action spectrum for a standard (phakic) eye, and $A(\lambda)$ (aphakic eye) as recommended by CIE.[1]

Nowadays there are very few occurrences of aphakic eyes, since during cataract surgery once the crystalline lens has been removed, it is usually replaced with an IOL of similar power that plays the role of the crystalline lens. The first IOLs available in the market did not block UV radiation, and, as a consequence, the patient was exposed to BLH as if an aphakic. The IOLs available nowadays are provided with UV filters to cut off exposure below a specific wavelength, but in general they transmit much more violet and blue light than the crystalline lens does at any age and thus the potential for photochemical injury can be assumed.

The action spectrum for the BLH plays the role of a spectral weighting function, which has to be included in the calculations of the TLVs. Based on these values, one can then evaluate the potential for BLH or the recommended maximum exposure times for a given radiation source. Conventional broadband radiation sources emit a wide range of wavelengths, each of them presenting a different hazard to the retina regarding BLH only. Thus, the global BLH for a given source depends not only on the total radiant power emitted by the source but also on its relative spectral distribution. The relative hazard of a given radiation source is defined as follows:

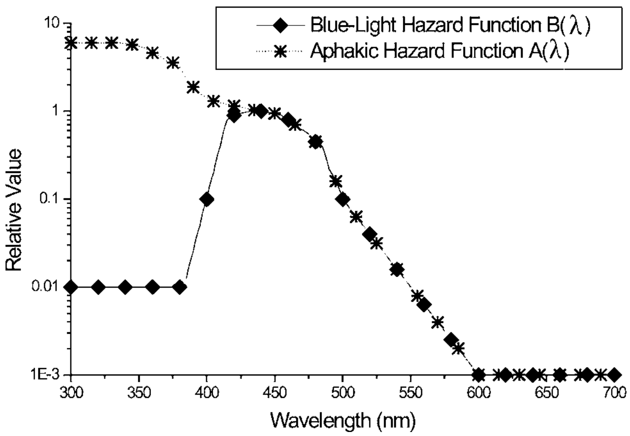

Fig. 1. Spectral weighting functions for retinal hazards $A(\lambda)$ (aphakic eye) and $B(\lambda)$ (normal eye).

$$X_{blue} = \sum_{305}^{700} X_{\lambda} B(\lambda) \Delta\lambda, \qquad (1)$$

where X_{λ} is the spectral radiance or spectral irradiance of the optical radiation source, $B(\lambda)$ is the BLH function that represents the relative spectral effectiveness for the BLH, and $\Delta\lambda$ is a wavelength interval at the center of which $B(\lambda)$ is defined and over which spectral irradiance or spectral radiance is measured.

The present work focuses on the evaluation of several models of IOLs. The spectral transmittance of various models of IOLs currently available in the market has been experimentally measured and compared with the average behavior found for the crystalline lens. Significant differences among the various IOLs were obtained, mostly regarding the cutoff wavelength. Similar studies have been published by various authors,[11–19] whose results follow the same trend as those obtained in the present work. The aim of this study was to assess the impact upon the action spectrum of the BLH derived from the use of IOLs and to evaluate the potential hazard for photochemical injury undergone by IOL wearers due to exposure to different radiation sources that may not be that dangerous for people who have not had their crystalline lens surgically removed.

Even though the study of how other visual and daily life functions could be affected by the use of these types of IOLs is not the objective of this paper, we consider that the method used to address the BLH problem could be useful to quantify other effects. Then we also present a first approach on the effect that the different IOL models studied in this work have on the potential reduction in scotopic vision, which has been discussed by several authors.[16–21]

2. SPECTRAL TRANSMITTANCE FOR INTRAOCULAR LENSES

Four models of commercial IOLs from different manufacturers were studied. Table 1 shows the main features of each IOL. As can be derived from the table, all four IOLs are equipped with a UV filter, and one of them (Acrysof Natural) also contains a blue filter.

The spectral transmittance for each IOL was experimentally measured by means of a PerkinElmer spectrophotometer (Model Lambda 900) in the 200–700 nm wavelength interval, with a bandwidth of 0.5 nm at steps of 1 nm. The IOLs selected from each model to be evaluated all had a similar power value (~20 D) in order to avoid any potential inconsistencies related to the geometry of the beam. The IOLs are distributed inside a sterile envelope that should be opened only under sterile conditions similar to those found in an operating room in order to guarantee a complete absence of contamination. However, the sterility conditions should not affect, in principle, the transmittance properties of the lens. The present study has been carried out in a standard optics laboratory, which does not meet the requirements to be considered a sterile one. Two sets of measurements were recorded for each lens under different conditions: immersed in a saline solution and mounted directly on air. Different results regarding absolute values of transmittance have been found between these measurement conditions. This can be explained by the existence of the Fresnel reflection coefficients associated with the air–IOL interface,[18] but no change is observed regarding the cutoff wavelength due to the immersion media, which is the most important aspect for the purpose of this work. Figure 2 shows an example of results obtained for transmittance values of the IOL identified as Istacryl when measured in saline solution and mounted directly in air.

Figure 3 shows the spectral transmittance curves obtained for each IOL inmersed in saline solution. As can be

Table 1. Intraocular Lens Characteristics

Manufacturers	Material	Filter	Name of Lens
Alcon	Acrylic	UV+blue	Acrysof natural
Bausch & Lomb	Hydrogel/PMMA	UV	Hydroview
Bausch & Lomb	Silicone elastomer/hydrophilic acrylic copolymer	UV	Akreos
LCA	Hydrophilic acrylic copolymer	UV	Istacryl

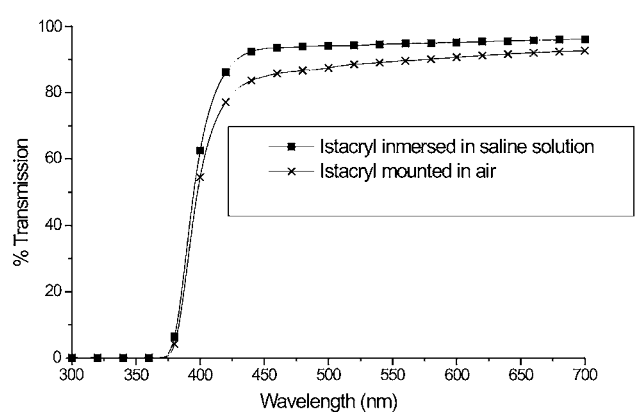

Fig. 2. Differences obtained in transmittance values for the IOL identified as Istacryl when measured in saline solution and mounted directly in air.

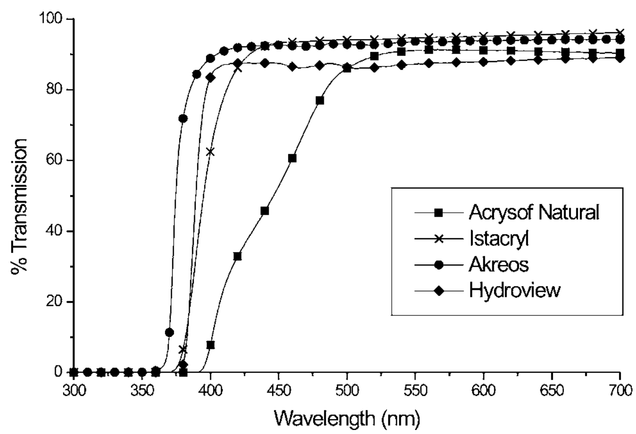

Fig. 3. Spectral transmittance for the IOLs under study.

seen from the figure, not only is the spectrum for the IOL with a blue filter (Acrysof Natural) substantially different from the rest, but there are also substantial differences among the three lenses equipped only with a UV filter, especially regarding the cutoff wavelength. They all show a complete absorption of UV-C (200–280 nm) and UV-B (280–320 nm); however, their behavior inside the UV-A range (320–400 nm) differs considerably. Only Acrysof Natural completely absorbs UV-A radiation, while the rest of the IOLs under analysis show different values for the cutoff wavelength, ranging from 350 nm (Akreos) to 370 or 380 nm (Istacryl and Hydroview, respectively).

3. COMPARISON WITH THE CRYSTALLINE LENS: IMPACT UPON THE ACTION SPECTRUM FOR THE BLH

In order to assess the need to adjust the action spectrum for the BLH for eyes implanted with IOLs, we need to compare in the first place the spectral transmittance curves obtained for these lenses with the curve that characterizes the crystalline lens. However, a wide variety of values for the crystalline transmittance are found in the literature[22–27] due to the strong dependence of the spectral transmittance of the crystalline lens on the age of the person. Nonetheless, and taking into account that the discrepancy between the two action spectra for the BLH discussed here [$A(\lambda)$ for aphakic eyes and $B(\lambda)$ for standard, phakic eyes] is due only to the effect of the crystalline lens, this means that the ideal spectral transmittance of the crystalline lens can be inferred by means of the $B(\lambda)$-to-$A(\lambda)$ ratio; that is,

$$B(\lambda) = \tau_{crystalline}(\lambda) \cdot A(\lambda). \tag{2}$$

The resulting spectral transmittance for the crystalline lens, as obtained from Eq. (2), is shown in Fig. 4, together with the curves for the IOLs under analysis (this time normalized to the maximum). The normalization has been chosen to obtain transmission unity in the maximum in order to compare it with the ideal transmission of the crystalline lens.

As can be inferred from the figure, three out of the four IOL models under analysis have a shorter cutoff wavelength than that for the crystalline lens. As previously mentioned, the crystalline lens acts as a weighting function upon the action spectrum for the aphakic eye in order to obtain the action spectrum curve for a normal (phakic) eye. In this sense, and just by reversing the above reasoning, it is possible to calculate the corrected action spectrum function for eyes implanted with IOLs if we know its spectral transmittance. Thus, applying Eq. (2) to each of the IOLs under study yields

$$B_{IOL}(\lambda) = \tau_{IOL}(\lambda) \cdot A(\lambda). \tag{3}$$

Figure 5 shows the resulting curves $B_{\mathrm{IOL}}(\lambda)$ for each IOL after applying Eq. (3) to the spectral transmittances that had been experimentally recorded.

The differences in transmittance among the different IOLs and with respect to the crystalline lens, especially regarding the cutoff wavelength, imply significant modifications of the corresponding action spectrum in the UV-A region. For longer wavelengths, the alterations to the action spectrum are very small or even nonexistent. As for the Acrysof Natural IOL, one can notice that its action spectrum for the blue range is significantly lower than that for the standard eye, due to the IOL being combined with a blue filter, as described in Table 1.

4. ASSESSMENT OF THE POTENTIAL HAZARD FOR DIFFERENT RADIATION SOURCES

When making use of the corrected action spectra for the BLH, it is very interesting to reassess the TLVs and the

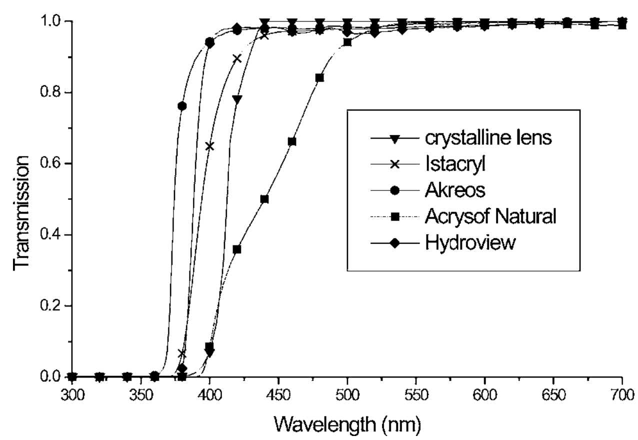

Fig. 4. Transmittance curves (normalized values) of the IOLs under study in comparison with the ideal transmittance of the crystalline lens.

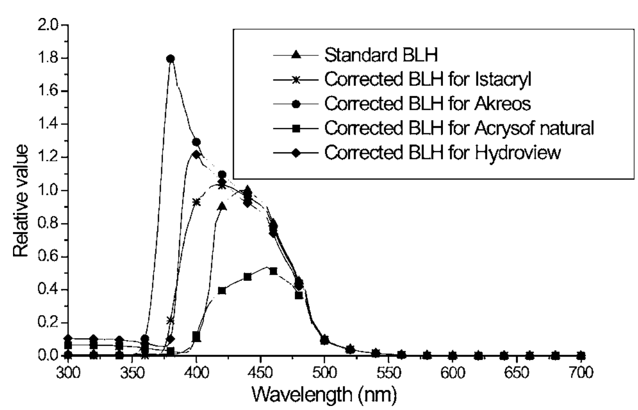

Fig. 5. Standard action spectrum for BLH and corrected action spectra computed for each IOL.

Table 2. Hazard Factor (X_{blue}) for Various Radiation Sources as Obtained Both from the Standard Action Spectrum for the BLH and the Four Corrected Action Spectra Calculated for the Different IOLs under Analysis

Radiation Source	Standard BLH	Corrected BLH for Istacryl	Corrected BLH for Akreos	Corrected BLH for Acrysof Natural	Corrected BLH for Hydroview
Illuminant A	11.42	12.95	15.08	7.48	13.15
Illuminant D65	60.57	74.45	93.35	38.10	78.28
Solar Irradiance 1	59.58	72.77	91.03	37.49	76.14
Solar Irradiance 2	60.15	73.53	92.04	37.80	76.87
Solar Irradiance 3	20.26	21.99	23.85	13.17	21.88
High-pressure mercury vapor lamp	2.70	3.65	5.17	1.58	4.04
Compact fluorescent lamp	3.79	4.32	4.73	2.22	4.37

maximum exposure times for several standard radiation sources: In this sense, if we replace in Eq. (1) the corrected $B(\lambda)$ function (the ones shown in Fig. 5) and we include the corresponding relative irradiance curve for the radiation sources under analysis (each having a different spectral content in the UV region), it is possible to calculate the potential hazard that each source presents to wearers of the different IOLs as compared with the potential hazard of the sources for a person whose crystalline lens has not been extracted.

The radiation sources of choice for the present study were the following:

- CIE standard illuminants A and D65.[28]
- Three direct solar irradiance spectra.
- Compact fluorescent lamp.
- High-pressure mercury vapor lamp.

The direct solar irradiance spectra were obtained by means of the SMARTS2 model (Version 2.9.2; single model for atmospheric transmission of sunshine) by Gueymard[29] and by using different input atmospheric conditions. In this case, to generate the three spectra, we modified the relative air mass, the turbidity factor, and the ozone content.

On the other hand, the spectra for the fluorescent lamp and for the mercury vapor lamp were experimentally computed in our laboratory by means of a UV-VIS spectroradiometer.[30]

Table 2 shows the corresponding hazard factor (X_{blue}) obtained for each radiation source under study and for each IOL (i.e., for each corrected action spectrum).

According to these values, all the IOLs except for the Acrysof Natural (which incorporates a blue filter in combination with the UV filter) have associated hazard factors (X_{blue}) that are significantly higher as those for a standard eye (i.e., an eye whose crystalline lens has not been removed). To permit an easier comparison, Table 3 shows the same data as in Table 2 but normalized to the corresponding hazard factor for the standard eye. That is, it displays the $X_{blue(IOL)}/X_{blue(BLH\ standard)}$ ratio.

With the exception of the Acrysof Natural IOL, whose associated hazard factor is between 35% and 42% lower than that for the standard eye, depending on the radiation source, the rest of the IOLs induce a significant increase of the hazard factor. It is worth emphasizing the fact that for the Akreos IOL, the associated hazard factor increases up to 91% with respect to the standard eye for radiation sources having a high relative UV content; even sources with a lower UV content, like an incandescence lamp (Illuminant A) or the solar daylight (Illuminant D65) can involve a hazard factor between 32% and 54% higher than that for a standard eye.

Table 3. Relative Hazard Factor $X_{blue(IOL)}/X_{blue(BLH\ standard)}$

Radiation Source	Istacryl	Akreos	Acrysof Natural	Hydroview
Illuminant A	1.13	1.32	0.65	1.15
Illuminant D65	1.22	1.54	0.62	1.29
Solar Irradiance 1	1.22	1.52	0.62	1.27
Solar Irradiance 2	1.22	1.53	0.62	1.27
Solar Irradiance 3	1.08	1.17	0.65	1.08
High-pressure mercury vapor lamp	1.35	1.91	0.58	1.49
Compact fluorescent lamp	1.14	1.24	0.58	1.15

5. SCOTOPIC SENSITIVITY AND INTRAOCULAR LENSES

Controversy has arisen in recent years over the use of IOLs equipped with a blue filter. Several previously published papers[16–21] suggested an important reduction in light entering the eye with use of this type of IOL under scotopic conditions. Although to identify and/or quantify this effect correctly would be the subject of a separate work, we present here a first approach obtained on the basis of an analysis similar to that realized with the BLH.

To be able to quantify correctly the effect that the different IOLs could have on scotopic sensitivity, it is necessary to know the particular action spectrum of this function. In the case of a phakic eye, this function is perfectly well known and tabulated by the CIE[31] [$V'(\lambda)$ function]. For aphakic observers, although in the literature it is possible to find some measurements on aphakic scotopic response,[32] it does not exist as a function recognized as an international standard. Nevertheless, if we consider again that the difference between the two action spectra is due only to the effect of the crystalline lens, using the "ideal" transmittance curve previously obtained, we could quantify the effect that the IOLs studied have on scotopic vision.

Thus assuming that $V'_{phakic}(\lambda)=\tau_{crystalline}(\lambda)\cdot V'_{aphakic}(\lambda)$, we can first calculate the "ideal" curve for $V'_{aphakic}$ and later replace the transmittance of the crystalline lens with the corresponding transmittance of each IOL under study to evaluate the effect of each on scotopic vision.

We have made calculations in the described form, and we have obtained that the blue-blocking IOL (with a power value of 20 D) decreases scotopic sensitivity by 14%. Negligible reduction has been obtained for the rest of the IOLs under study. Similar results have been reported by other authors[17–21] that seem to indicate the validity of the proposed method.

6. CONCLUSIONS

The optical properties of intraocular lenses (IOLs) should ensure not only a good optical quality but also a degree of protection against potentially hazardous radiation sources that is similar to that provided by the removed crystalline lens. In the present work we have analyzed the influence of various commercially available IOLs upon the so-called blue-light hazard (BLH).

The significant differences found in the transmittance spectra for the different IOLs among themselves as well as with respect to the expected transmittance for the crystalline lens make it necessary to apply a correction factor to the action spectrum for the BLH associated with each IOL. Even though the differences with respect to the standard eye are not as dramatic as those for the aphakic eye, the corrected action spectra for the IOLs presents higher values than those for the standard eye in the short-wavelength range as a result of the shorter cutoff wavelength.

As a consequence, IOL wearers using the IOL models under study will be more exposed to BLH, particularly for radiation sources with a high-UV and short-visible-wavelength content. The increase of the hazard factor with respect to a standard eye is very significant and noteworthy for some of the IOLs under study not only when exposed to radiation sources having a high-UV content but even for other radiation sources often used as an illumination source.

Other visual and daily life functions may be affected by IOLs, and we think that the method proposed in this paper can be used to evaluate the changes to be introduced in the respective action spectrum. As an example, we have presented a first approach on the potential reduction of scotopic sensitivity derived from the use of the different types of IOLs studied. From those results, we want to emphasize the need to have an international standard that represents scotopic luminous efficiency for aphakic observers in order to correctly evaluate the effect that the different existing IOLs can have.

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