EXTENDED REPORT

The effect of chromatic dispersion on pseudophakic optical performance

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Aim: Monochromatic and chromatic aberrations limit the visual performance of pseudophakic eyes. Chromatic aberration is caused by the chromatic dispersion of optical materials which can be characterised by their Abbe numbers. This study examines how chromatic dispersion affects pseudophakic optical performance at different wavelengths and spatial frequencies.

Methods: Abbe numbers were measured for acrylic and silicone intraocular lenses (IOLs). A schematic eye model based on cataract population data was used to compute monochromatic and photopic polychromatic modulation transfer functions (MTFs) for pseudophakic eyes with aspheric IOLs. IOL Abbe numbers were varied without changing other eye model parameters to determine how chromatic dispersion affects pseudophakic MTF and chromatic difference of refraction. Additional calculations were performed for (1) acrylic or silicone materials and (2) high-pass optical filters blocking either UV radiation or UV radiation and short wavelength visible light.

Results: Shorter wavelengths account for approximately two thirds of pseudophakic chromatic difference of refraction or longitudinal chromatic aberration. Increasing Abbe number (reducing chromatic dispersion) decreases total chromatic difference of refraction and increases photopic polychromatic MTF. For a specific spatial frequency, there is an effective pseudophakic depth of wavelength over which a particular MTF level is achieved or exceeded. Depth of wavelength narrows with decreasing Abbe number or increasing spatial frequency. Blue-blocking IOL chromophores improve photopic MTF performance by less than 1.5%.

Conclusions: Most pseudophakic longitudinal chromatic aberration arises from the chromatic dispersion of IOLs rather than the cornea and other ocular media. Increasing the Abbe number of optic materials improves overall pseudophakic optical performance. Optical transmission of medium and high spatial frequency modulation information has a spectrum similar to photopic luminous efficiency, accounting for the inability of blue-blocking chromophores to improve photopic pseudophakic contrast sensitivity significantly and demonstrating the excellent mutual adaptation of modulation transfer by the eye's optics and management of that data by the retina and brain.

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Pseudophakic optical performance is limited by light scattering foci or surfaces, ocular media inhomogeneities, pupillary diffraction, and monochromatic or chromatic aberrations of the cornea and intraocular lens (IOL). Chromatic dispersion is the variation of an optical material's index of refraction with wavelength.^{1,2} It causes different wavelengths to be focused at (1) different axial positions (longitudinal chromatic aberration) and (2) different lateral positions in the same transverse plane (transverse chromatic aberration).¹ Dispersion also produces chromatic differences of refractive error, image size and image position.³ Implanted IOLs with higher chromatic dispersion produce greater longitudinal chromatic aberration in pseudophakic eyes.^{4,5}

The Abbe number (V value) characterises an optical material's chromatic dispersion.⁶ It is defined as: $V_d = (n_d - 1)/(n_F - n_C)$ where n_d , n_F , n_C are a material's refractive index at 587, 486 and 656 nm, respectively. Materials with lower chromatic dispersion generally have larger Abbe numbers (the denominator in the definition of V_d is smaller). Refractometers and goniometers can be used to measure Abbe numbers, which range from 35 to 60 for contemporary IOL materials.⁴

Schematic ray-tracing models of the human eye use anatomic and optical data.⁷ Polychromatic modulation transfer functions (MTFs) contain information on both monochromatic and chromatic aberrations.^{8,9} We measured the Abbe numbers of typical IOL optic materials and used a cataract-population-based schematic eye model^{10,11} to examine how IOL chromatic

dispersion affects pseudophakic optical performance at different wavelengths and spatial frequencies.

METHODS

An ATAGO multi-wavelength reflection-type Abbe refractometer (ATAGO Ltd, Tokyo, Japan) was used to measure the Abbe numbers of acrylic (Tecnis ZA9003 (Advanced Medical Optics, Santa Ana, CA, USA); AcrySof SA60AT and SN60AT (Alcon Laboratories, Fort Worth, TX, USA) and YA60BB (Hoya, Tokyo, Japan)) and silicone (Tecnis Z9002 (Advanced Medical Optics)) IOLs. Three independent measurements were performed for each lens. Measurement accuracy was ± 0.0002 for refractive index and ± 0.1 for Abbe number. Averaged results are presented in table 1 and used to guide our sensitivity analysis.

Photopic polychromatic modulation transfer functions (MTFs) were calculated for a pseudophakic human eye from a photopic-weighted superposition of monochromatic optical transfer functions normalised by total photopic luminous sensitivity,⁹ using the ZEMAX optical design program (ZEMAX Development Corporation, Bellevue, WA, USA), the Holladay-Piers schematic eye,^{10,11} Tecnis IOL parameters (Advanced Medical Optics) and 32 equal 10 nm photopic luminous efficiency¹² spectral bands between 380 and 700 nm.

Abbreviations: CSF, contrast sensitivity function; IOL, intraocular lens; MTF, modulation transfer function

Table 1 Refractive indices and Abbe numbers for different lenses and optical materials

Intraocular lens	Index of refraction	Abbe number
Alcon acrylic*	1.55	37
AMO acrylic†	1.47	55
AMO silicone‡	1.46	42
Hoya acrylic§	1.51	43
Crystalline lens ²	1.40	47

*AcrySof SA60AT or SN60AT, Alcon Laboratories, Fort Worth, TX, USA.

†Tecnis ZA9003, Advanced Medical Optics, Santa Ana, CA, USA.

‡Tecnis Z9002, Advanced Medical Optics.

§Hoya YA60BB, Hoya, Tokyo, Japan.

Chromatic difference of refraction was computed using wavefront data from the schematic eye, the Optical Society of America's Zernike polynomial definition, and magnification calculations truncated at the sixth Zernike order.¹³

The Holladay-Piers schematic eye model uses data on the average refractive power and spherical aberration of a cataract population.^{10–11} Its predictions are similar to those of the Liou-Brennan¹⁴ schematic eye if an IOL is substituted for the Liou-Brennan model's crystalline lens. We used a Holladay-Piers schematic eye with (1) a two-surface cornea having a central 0.5 mm thickness and (2) Atchison and Smith's Abbe number data of 55.5, 50.4 and 51.3 for the cornea, aqueous and vitreous, respectively.² The distance between the anterior surfaces of the cornea and IOL was 4.5 mm. Axial length was optimised for emmetropia at 550 nm. Overall spherical aberration of the Holladay-Piers schematic eye is zero at 550 nm with a Tecnis IOL.¹⁰

We performed a sensitivity analysis of photopic polychromatic MTFs using an IOL refractive index of 1.46 and keeping all eye model parameters invariant except for the Abbe number of the IOL. Abbe numbers from 35 to 70 were used to span the chromatic dispersion range of current IOL optical materials. An

Figure 1 Chromatic difference of refraction between 400 and 700 nm for pseudophakic eyes with a 3 mm pupil diameter, an IOL refractive index of 1.46 and IOL Abbe numbers of 35, 47, 55, 70 and 200. Best focus is shifted from 550 nm to 590 nm to permit comparison with Atchison and Smith data for phakic human eyes which is also shown (A&S) for comparison.² Pseudophakic chromatic difference of refraction for an IOL with an Abbe number of 200 is due primarily to ocular media because the chromatic dispersion of the IOL is negligible in this near diffraction-limited state.

Abbe number of 200 was used to simulate the near diffraction-limited condition of an IOL with negligible chromatic dispersion. Additional calculations were performed for IOLs with (1) optical filters¹⁵ (chromophores) that attenuate either UV radiation (Tecnis Z9002, Advanced Medical Optics) or UV+violet+blue light (AcrySof SN60AT, Alcon Laboratories) and (2) acrylic or silicone optic materials (see table 1).

RESULTS

Spectral chromatic difference of refraction characterises the wavelength dependence of longitudinal chromatic aberration.¹ We calculated pseudophakic chromatic difference of refraction for IOL Abbe numbers of 35, 47, 55, 70 and 200. Results are presented in figure 1 for a 3 mm pupil diameter, with best focus shifted from 550 nm to 590 nm to permit comparison with Atchison and Smith's phakic human eye data.² The human crystalline lens' Abbe number² is 46–47. Figure 1 shows that our computed pseudophakic chromatic difference of refraction results with an IOL Abbe number of 47 are similar to Atchison and Smith's data for normal human eyes.

Total chromatic differences of refraction between 380 and 700 nm for IOL Abbe numbers of 35, 47, 55, 70 and 200 are 2.8, 1.9, 1.4, 0.92 and 0.20 dioptres, respectively. Confusion may arise if the cornea and IOL are considered as independent optical components rather than components coupled coherently¹⁶ to each other and ocular media. For example, if the total chromatic aberration of the cornea and lens are considered independent of each other and adjacent ocular media, then (1) the cornea has a total chromatic difference of refraction of 1.2 dioptres and (2) IOLs with Abbe numbers of 35, 47 and 200 have total chromatic differences of refraction of 3.8, 2.9 and 0.7, respectively. Thus, the overall chromatic difference of refraction of a pseudophakic eye can be smaller than that of its independent cornea and crystalline lens components.

An IOL with an Abbe number of 200 has no significant chromatic dispersion, so the pseudophakic eye's remaining 0.20 dioptre total chromatic difference of refraction is due primarily to the chromatic dispersion of cornea and other ocular media rather than the IOL. We repeated our calculations for an IOL Abbe number of 200 using the optical parameters of the Liou-Brennan and Atchison schematic eyes. The total chromatic difference of refraction was 0.22 and 0.10 for the Liou-Brennan and Atchison eye models, respectively, similar to our 0.20 dioptre Holladay-Piers schematic eye model result.

Figure 1 also shows that shorter wavelengths cause most longitudinal chromatic aberration. This finding is quantified in figure 2, which presents total chromatic difference of refraction for short (380–500 nm), medium (500–600 nm), long (600–700 nm) and overall (380–700 nm) wavelength regions. Short wavelengths account for roughly two thirds of chromatic difference of refraction or longitudinal chromatic aberration of higher chromatic dispersion IOLs.

Polychromatic MTFs provide insight into the potential effects of IOL and ocular media chromatic dispersion on clinical parameters such as pseudophakic contrast sensitivity and visual acuity. Figure 3 presents MTFs for spherical aberration correcting IOLs that differ only in their Abbe numbers. It shows that higher IOL Abbe numbers (lower chromatic dispersion) produce better photopic pseudophakic optical performance with otherwise equivalent IOL parameters. For small Abbe numbers, performance is better for 3 mm than 5 mm pupil diameters because chromatic and monochromatic aberrations are both present, consistent with previous clinical and experimental findings.^{3–4} Conversely, for an Abbe number of 200, chromatic aberration is negligible and performance is better for 5 mm than 3 mm pupil diameters because of near diffraction-limited conditions.

Figure 2 Total chromatic difference of refraction for short (380–500 nm), medium (500–600 nm), long (600–700 nm) and overall (380–700 nm) wavelengths. Abbe numbers ranging from 35 to 200 are shown. Calculations are shown for a 3 mm pupil diameter. Short wavelengths account for roughly two thirds of the total chromatic difference of refraction for IOLs with smaller Abbe numbers.

Intraocular lens chromatic dispersion affects the spectral and spatial frequency behaviour of MTFs of a pseudophakic eye. Figure 4 presents photopic-weighted monochromatic MTF data at different wavelengths for a 5 mm pupil diameter and Abbe numbers of 35, 70 and 200. MTF performance is optimal around 550 nm because of IOL design. MTF values fall as IOL Abbe numbers decrease from 200 to 35. Calculations using scotopic luminous efficiency¹⁷ produce similar results, although MTF performance peaks around 510 nm rather than 550 nm.

Photopic pseudophakic MTFs for a particular spatial frequency decrease as the distance in optical wavelength from 550 nm increases, consistent with prior analysis showing that target visibility is dominated by wavelengths which are only slightly defocused.^{18–19} Thus, there is a pseudophakic *depth of wavelength*, a range of wavelengths over which a particular MTF level is achieved or exceeded for a specific spatial frequency. Depth of wavelength narrows (1) as spatial frequency increases for a particular IOL Abbe number or (2) as Abbe number decreases (chromatic aberration increases) for a particular spatial frequency. Narrowing of depth of wavelength with increasing spatial frequency for a particular Abbe number is also evident in figure 5, which presents monochromatic MTF data without photopic weighing for an Abbe number of 47 and a 5 mm pupil diameter. The spectral dependence of medium and high spatial frequencies resembles photopic sensitivity, even though monochromatic MTFs were computed independent of photopic luminous efficiency data.

Figures 4 and 5 show that the optical performance of a pseudophakic eye is determined at medium and high spatial frequencies primarily by wavelengths between 500 and 600 nm, which are focused better than shorter or longer wavelengths. Thus, blue-blocking IOL chromophores would be ineffective in improving photopic contrast sensitivity in this spatial frequency range, even though short wavelengths cause most chromatic difference of refraction (see fig 2). This conclusion is quantified in figure 6, which shows the percentage improvement in MTF afforded by UV+violet+blue blocking IOL chromophores in comparison to standard UV-only blocking chromophores. The percentage improvement for IOL Abbe numbers of 35, 70 and 200 is less than 1.5%, considerably smaller than the 40% estimated to be needed²⁰ for a measurable improvement in contrast sensitivity. Thus, short wavelength blocking chromophores do not compensate for the

Figure 3 Photopic polychromatic MTFs for an IOL refractive index of 1.46 and Abbe numbers of 35, 70 and 200. Results for 3 mm and 5 mm pupil diameters are shown. IOLs with higher Abbe numbers (lower chromatic dispersion) have better optical performance and potential contrast sensitivity (the magnitude of the contrast sensitivity function is proportional to the product the MTF and the retinal-neural transfer function in Fourier space^{22–23}) when IOL parameters are otherwise equivalent.

reduced performance of lower Abbe number optic materials, which was illustrated in figure 3.

Figure 7 illustrates how schematic eye models can be used to estimate the relative optical performance of comparable IOLs that correct for spherical aberration but are fabricated from different optic materials. MTFs are shown for a silicone and two acrylic IOLs that differ in their optical design by the radii of curvature of their anterior surfaces which were chosen to provide zero spherical aberration for the optic materials in table 1. MTF performance improves with increasing Abbe number, as in figure 3. The MTF of the larger Abbe number acrylic material in figure 7 is 40% higher than the smaller Abbe number acrylic material at 30 cycles/degree (0.30 vs 0.42).

Figure 4 Photopic-weighted, monochromatic pseudophakic MTF values for an IOL refractive index of 1.46, a 5 mm pupil diameter and IOL Abbe numbers of 35, 70 and 200. For a specific spatial frequency, there is an effective pseudophakic *depth of wavelength*, a range of wavelengths over which a particular MTF level is achieved or exceeded. Depth of wavelength narrows with (1) increasing spatial frequency for a particular IOL Abbe number or (2) decreasing Abbe number (increasing chromatic aberration) for a particular spatial frequency. Wavelengths below 500 nm contribute little to pseudophakic photopic optical performance for contemporary optic materials.

Figure 5 Pseudophakic monochromatic MTFs without photopic weighting for a 5 mm pupil diameter and an intraocular lens with an Abbe number of 47 and a refractive index of 1.46. Effective transfer of medium and high spatial frequency modulation information is limited to the central part of the visible spectrum, demonstrating an excellent spectral match between ocular optics and photopic visual sensitivity.

DISCUSSION

Chromatic dispersion of ocular media and IOL materials produces longitudinal chromatic aberration, which may degrade the quality of the pseudophakic retinal image.^{4, 5, 21} Thinner, higher index of refraction optical materials are useful for small incision cataract surgery, but they generally have larger chromatic dispersion, as characterised by their smaller Abbe numbers. Table 1 shows this relationship for silicone and acrylic materials.

Total pseudophakic chromatic dispersion increases with decreasing IOL Abbe number, as figure 1 shows for a silicone optic with a 1.46 refractive index. An IOL with an Abbe number of 47, comparable to that of the crystalline lens, produces pseudophakic longitudinal chromatic aberration similar in magnitude and spectral dependence to that of phakic eyes. An IOL with negligible chromatic aberration produces minimal overall pseudophakic longitudinal chromatic aberration, demonstrating that most pseudophakic chromatic aberration arises from chromatic dispersion of optic material rather than the cornea and other ocular media.

Polychromatic MTFs embody both monochromatic and chromatic aberrations. The eye's optics are coupled incoherently to neural processing by the retina and brain.¹⁶ The overall contrast sensitivity function (CSF) can be expressed as the product of transfer functions representing the eye's optical (MTF) and retinal-neural (NTF) processing.^{16, 22–24} Thus, (1) the percentage change in CSF caused by an optical variable is proportional to the percentage change in MTF caused by that variable (the actual magnitude of the change depends on a variety of eye-specific parameters), and (2) changes in polychromatic MTFs provide insight into concomitant CSF alterations.

Pseudophakic photopic MTF values are highest around 550 nm, as shown in figure 4. They decrease at lower or higher optical wavelengths due to optical defocus and reduced photopic luminous efficiency. In essence, this pseudophakic depth of wavelength is a spectral band-pass filter, limiting effective contrast transfer to optical wavelengths in the central part of the visible spectrum. Figure 5 for monochromatic MTF data without photopic weighting shows the same spectral dependence for medium and high spatial frequencies, demonstrating an

Figure 6 The percentage improvement in photopic polychromatic MTF provided by a UV+violet+blue attenuating spectral filter in comparison to a conventional UV blocking IOL filter. Results are shown for an IOL refractive index of 1.46, a 5 mm pupil diameter and IOL Abbe numbers of 35, 70 and 200. Spectral filters have a greater effect with lower Abbe number (higher chromatic dispersion) optic materials, but the magnitude of the percentage improvement across this broad range of chromatic dispersions is less than 1.5%, considerably smaller than the 40% estimated to be needed²⁰ for clinical significance.

excellent spectral match between this purely optical effect and photopic visual sensitivity.

The relative unimportance of violet and blue light (400–500 nm) in the transfer of medium and high spatial frequency modulation information accounts for the minimal effect of short wavelength blocking filters on photopic pseudophakic optical performance, as illustrated in figure 6 and demonstrated in clinical studies showing no significant difference between the contrast sensitivity of pseudophakes with and without blue-blocking IOL chromophores.^{25–28}

Varying IOL Abbe number without changing other schematic eye parameters reveals how chromatic dispersion affects pseudophakic optical performance. Modern IOL materials provide different combinations of Abbe numbers and refractive indices, as presented in table 1. Figure 7 shows how chromatic dispersion affects the overall pseudophakic performance of

Figure 7 MTFs for a silicone and two acrylic IOLs that differ in their optical design by the radii of curvature of their anterior surfaces, which were chosen to provide zero spherical aberration for their optic materials (see table 1). Each curve is labelled with the Abbe number and refractive index of the optic material. A 3 mm pupil diameter was used in all calculations. MTF performance improves with increasing Abbe number, as in figure 3. The MTF of the larger Abbe number acrylic material is 40% higher than the smaller Abbe number acrylic material at 30 cycles/degree (0.30 vs 0.42).

spherical aberration correcting IOLs. As in figure 3, optical performance improves as Abbe number increases (chromatic dispersion decreases).

In summary, pseudophakic longitudinal chromatic aberration is caused primarily by the chromatic dispersion of IOLs rather than the cornea and other ocular media. Pseudophakic performance improves with increasing Abbe number when IOL parameters are otherwise equivalent. Higher Abbe number acrylic materials provide better optical performance in spherical aberration correcting IOLs. Chromatic depth of wavelength narrows with decreasing Abbe number. The spectra of pseudophakic MTF data for medium and high spatial frequencies resemble photopic sensitivity, showing that the transfer of modulation information by ocular optics is well matched to the capture and management of those data by the retina and brain, so ocular optics recapitulate visual psychophysics.

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