In vivo subjective and objective longitudinal chromatic aberration in patients bilaterally implanted with same design of hydrophobic and hydrophilic intraocular lenses

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PURPOSE: To measure the longitudinal chromatic aberration in vivo using psychophysical and wavefront-sensing methods in patients bilaterally implanted with monofocal intraocular lenses (IOLs) of similar aspheric design but different materials (hydrophobic, Podeye and hydrophilic, Poday).

SETTING: Instituto de Optica, Consejo Superior de Investigaciones Cientificas, Madrid, Spain.

DESIGN: Prospective observational study.

METHODS: Measurements were performed with the use of psychophysical (480 to 700 nm) and wavefront-sensing (480 to 950 nm) methods, using a custom-developed adaptive optics system. Chromatic difference-of-focus curves were obtained from best-focus data at each wavelength, and the longitudinal chromatic aberration was obtained from the slope of linear regressions to those curves.

RESULTS: The longitudinal chromatic aberration from psychophysical measurements was 1.37 diopters (D) $\pm$ 0.08 (standard deviation) (hydrophobic) and 1.21 $\pm$ 0.08 D (hydrophilic); from wavefront-sensing longitudinal chromatic aberration was 0.88 $\pm$ 0.07 D and 0.73 $\pm$ 0.09 D, respectively. In 480 to 950 nm, longitudinal chromatic aberration was 1.27 $\pm$ 0.09 D (hydrophobic) and 1.02 $\pm$ 0.13 D (hydrophilic). Longitudinal chromatic aberration was consistently higher in eyes implanted with the hydrophobic than the hydrophilic IOL (a difference of 0.16 and 0.15 D, respectively). Similarly to findings in young phakic eyes, longitudinal chromatic aberration from the psychophysical method is consistently higher than from wavefront-sensing, by 0.48 D (35.41%) for the hydrophobic and 0.48 D (39.43%) for the hydrophilic.

CONCLUSION: This study provides estimates of the longitudinal chromatic aberration measured in a wider spectral range than that in previous studies, using psychophysical and wavefront-sensing measurements.

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In natural conditions, with polychromatic light, retinal image quality is affected both by monochromatic and chromatic aberrations of the ocular optics and their interactions. Chromatic aberration in the eye arises from the wavelength dependence of the refractive index of the ocular media (chromatic dispersion) affecting diffraction, scattering, and aberrations.[1–3] Chromatic dispersion causes short wavelengths to focus in front of long wavelengths, producing a chromatic difference of focus between

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the shorter and longer wavelengths known as longitudinal chromatic aberration.[4] The interactions between chromatic and monochromatic aberrations have drawn attention, particularly as the magnitude and pattern of either aberration can be altered when the crystalline lens of the eye is replaced by an intraocular lens (IOL). In phakic eyes, it has been shown that monochromatic aberrations play a protective role against chromatic aberrations.[5,6] This opens the discussion of whether correction of both chromatic and monochromatic aberrations are needed to improve visual performance.[7]

In phakic eyes, longitudinal chromatic aberration has been widely studied, and it is fairly accepted that it is rather constant across the population and with age.[8,9] However, the reported longitudinal chromatic aberration varies across studies, probably associated with differences in the measurement techniques, psychophysical[4,9–14] and reflectometric,[15–19] as well as the spectral range under test. In a recent study,[20] we presented longitudinal chromatic aberration measured in the same subjects using psychophysical and reflectometry techniques in a wide spectral range (450 to 950 nm) with adaptive optics control of the subjects' natural aberrations. The longitudinal chromatic aberration measured psychophysically was significantly higher than that from reflectometry techniques (1.51 diopters [D] versus 1.00 D in the 480 to 700 nm range).

In recent years, monofocal IOL designs have improved not only to restore transparency or to correct refractive errors (sphere and cylinder) but also to reduce the spherical aberration of the eye.[21–25] However, the replacement of the IOL also modifies the chromatic dispersion properties of the eye, as this is affected by the refractive index wavelength dependency of the IOL material. Therefore, the optical performance of the pseudophakic in polychromatic light will be determined by both the IOL design and the IOL material.

The impact of the chromatic aberrations in the pseudophakic eye has been acknowledged.[26–28] There are even proposals for IOL (diffractive) designs aiming at correcting the ocular longitudinal chromatic aberration.[29,30] The dispersion properties of the IOL are defined by the Abbe number (ranging in most of designs from 35 to 60). The higher the Abbe number, the lower the longitudinal chromatic aberration. Most reports of longitudinal chromatic aberration and polychromatic optical quality in pseudophakic eyes are based on computational predictions on eye models and the IOL material Abbe number.[26,30,31] There are very few studies reporting in vivo measurements of longitudinal chromatic aberration of pseudophakic eyes. Nagata et al.[27] measured the longitudinal chromatic aberration in vivo (500 to 650 nm) in pseudophakic eyes implanted with poly(methyl methacrylate) and acrylic IOLs, using a modified chromoretinoscopy system.[32] Perez-Merino et al.[33] reported monochromatic aberrations measured at 2 wavelengths (532 nm and 785 nm) in 2 groups of pseudophakic eyes implanted with 2 IOLs (Tecnis, Abbott Medical Optics, Inc. and Acrysof IQ, Alcon Laboratories, Inc.) of different materials and found statistical differences between the chromatic difference of focus with the 2 IOL types (0.46 D and 0.75 D, respectively), consistent with the Abbe number of the IOL materials. Siedlecki et al.[34] presented the chromatic difference of focus in pseudophakic eyes implanted with 2 types of Acrysof IOLs (IQ SN60WF, spherical asymmetric biconvex IOL and the SA60AT, aspheric asymmetric biconvex IOL) measured at 470 nm, 525 nm, and 660 nm with the use of an autorefractometer adapted to monochromatic measurements of refraction.

In this study, we present in vivo longitudinal chromatic aberration in pseudophakic patients bilaterally implanted with monofocal aspheric hydrophobic and hydrophilic IOLs. Measurements were performed on patients using psychophysical and wavefront-sensing methods on a custom-developed adaptive optics platform, provided with a super-continuum laser source, a psychophysical channel, a Hartman-Shack wavefront sensor, and an electromagnetic deformable mirror to allow control of monochromatic natural aberrations. The psychophysical longitudinal chromatic aberration was obtained in the visible range (480 to 700 nm) and the longitudinal chromatic aberration from wavefront-sensing was obtained both in the visible (480 to 700 nm) and near infrared (IR) ranges

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FLA 5.4.0 DTD ■ JCRS9051_proof ■ 20 November 2015 ■ 1:57 pm

(700 to 900 nm). Chromatic difference of focus curves were obtained from best focus data at each wavelength in each experiment, and the longitudinal chromatic aberration was obtained from the slope of linear regressions to those curves. The measured longitudinal chromatic aberration was compared between eyes of the same patient, with longitudinal chromatic aberration values obtained on young phakic patients performed with the use of the same experimental system and with longitudinal chromatic aberration reported on pseudophakic patients in the literature.

PATIENTS AND METHODS

The longitudinal chromatic aberration was obtained from psychophysical and wavefront-sensing measurements of best focus at 8 different wavelengths on 18 eyes from 9 patients bilaterally implanted with the same design but different material IOLs (hydrophobic, the Podeye and hydrophilic, the Poday, PhysIOL) in each eye. Measurements were performed using a custom-developed polychromatic adaptive optics system.

Patients and Intraocular Lenses

Nine patients (mean age 73.92 years ± 4.28 standard deviation [SD]) participated in the study. Table 1 shows the age, refractive, and clinical profiles of the participants.

All patients were bilaterally implanted, 1 eye with the hydrophobic double-C loop hydrophobic IOL, and the contralateral eye with the hydrophilic IOL. Both IOLs are monofocal and aspheric, but they differ in their material. Table 2 shows the characteristics of the 2 IOL types.

Patients received a complete ophthalmic evaluation prior to enrollment in the study and surgery at the Instituto de Oftamología Avanzada, Madrid, Spain. The preoperative examination included uncorrected (UDVA) and corrected distance visual acuity (CDVA), using the Early Treatment of Diabetic Retinopathy Study (ETDRS) test, biomicroscopy, corneal topography (Nidek Co., Ltd), tonometry (Goldmann), and a fundus examination. Axial length, anterior chamber depth, and white-to-white were measured by means of optical biometry (IOLMaster, Carl Zeiss Meditec AG). The IOL power was calculated with the Holladay-2 formula, targeting emmetropia. The inclusion criterion for the study were good general health, no ocular pathology, no complications during surgery, IOL power between 18.00 D and 23.00 D, natural astigmatism less than 1.50 D, bilateral implantation, clear capsule, and postoperative CDVA better than 0.7. Surgeries in each eye were conducted with a time difference of less than 7 days, and the IOLs (hydrophobic or hydrophilic) were randomly assigned to the first or second eye.

Postoperative clinical evaluations were conducted at 1 day, 1 week, and 1 month after surgery and included UDVA and CDVA, using the ETDRS test, intraocular pressure (Goldmann), and biomicroscopy. At the 1-month follow-up visit, the visual quality was assessed in the clinic by the objective scatter index (OSI), modulation transfer function (MTF), and Strehl ratio, measured using the Optical Quality Analyzer System (OQAS, Visiometrics S.L.). Night haloes were measured using the Halo software (version 1.0, University of Granada). Surgical procedures were performed by 1 of 2 surgeons on an outpatient basis under topical anesthesia. For phacoemulsification, the surgeon made a 2.2 mm clear corneal incision. The IOLs were

Table 1. Optometric subjective refractions (spherical error, cylinder, axis) of the patients of the study, preoperatively and 1 month postoperatively.

				Preoperative Data				Follow-up (1 Month)			
Subject	Sex	Lens Implanted	IOL Power	Sph	Cyl	Axis	CDVA (LogMAR)	Sph	Cyl	Axis	DCVA (LogMAR)
S1_R_EYE	M	Podeye	21.50	3	−1	80	0.4	1.5	−1.25	80	0
S1_L_AY		Poday	22.50	4	−0.5	90	0.3	0	0	0	0
S2_R_AY	F	Poday	20.50	−0.75	−1	90	0.15	0	0	0	0
S2_L_EYE		Podeye	21.00	−1.75	−1.25	95	0.2	0	0	0	0.05
S3_R_EYE	F	Podeye	21.00	1.75	−1	55	0.3	0	−0.75	80	0
S3_L_AY		Poday	19.50	1.25	−1	115	0.2	0	−0.75	100	0
S4_R_AY	M	Poday	18.50	1.25	1.25	180	0.1	−1	0	0	0
S4_L_EYE		Podeye	18.00	0.75	−0.5	12	0.2	0	0	0	0
S5_R_AY	F	Poday	21.00	1.75	−1	90	0.2	0	0	0	0
S5_L_EYE		Podeye	20.50	1.25	−0.5	65	0.25	0	0	0	0
S6_R_EYE	M	Podeye	23.00	−2.75	−0.75	120	0.3	0	0	0	0
S6_L_AY		Poday	22.50	−3.25	−1	110	0.25	0	0	0	0
S7_R_EYE	F	Podeye	20.00	−1	−2.25	20	0.5	1	−1	180	0
S7_L_AY		Poday	21.50	0.5	−0.5	180	0.3	0	0	0	0
S8_R_EYE	F	Podeye	18.00	−2.75	−1.5	105	0.2	0.5	−1.5	95	0
S8_L_AY		Poday	19.50	0	−1	70	0.1	0.5	−1	75	0
S9_R_AY	F	Poday	19.00	−1	−0.5	70	0.2	0	−0.75	100	0
S9_L_EYE		Podeye	18.00	−1	−0.75	100	0.25	0.75	−0.5	70	0

Cyl = cylinder; S_AY = eyes implanted with PhysIOL Poday (hydrophilic); S_EYE = eyes implanted with PhysIOL Podeye (hydrophobic); Sph = spherical error.

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Table 2. Specifications of the Podeye and Poday IOLs provided by the manufacturer.

Model	Material	Design*	Asph. Aberration-Correcting	Hazardous Light Protection*	Packaging State*	RI	Abbe
Podeye[35]	Hydrophobic acrylic GF material	Monofocal, 1-piece, double C-loop	−0.11 μSA	UV/blue	Hydrated	1.52	∼41.91
Poday	Hydrophilic acrylic GF material	Monofocal, 1-piece, double C-loop	−0.11 μSA	UV/blue	Hydrated	1.46	∼58.00

GF = glistening free; RI = refractive index; UV = ultraviolet.
*Data from the intraocular lens specification.

implanted in the capsular bag with a single-use injection system (Microset, PhysIOL).

All participants were acquainted with the nature and possible consequences of the study and provided written informed consent. All protocols met the tenets of the Declaration of Helsinki and had been previously approved by the Spanish National Research Council (Consejo Superior de Investigaciones Científicas) Bioethical Committee. All experiments were conducted under mydriasis (tropicamide 1.0%, 2 drops 30 minutes prior to the beginning of the study and 1 drop every 1 hour).

Polychromatic Adaptive Optics Set-up

Measurements were conducted in a custom-developed adaptive optics system at the Visual Optics and Biophotonics Laboratory (Instituto de Óptica, Consejo Superior de Investigaciones Científicas) described in detail in a previous publication,[20] which allowed control of the aberrations of the subject while performing both psychophysical settings of best focus and wavefront aberration measurements at different wavelengths.

A super-continuum laser source (SC400 femtopower 1060, Fianium Ltd.) was used as the light source of the system, which allowed 2 independently filtered light fiber outputs (visible-channel: 480 nm, 532 nm, 550 nm, 650 nm, and 700 nm and near IR channel: 780 nm, 827 nm, and 950 nm) with a spectral bandwidth of approximately 5 nm (2 to 4 nm [visible]; 3 to 6 nm [near IR]). The laser power measured at the corneal plane ranged between 0.5 μW and 50 μW, within the American National Standards Institute safety limits at all wavelengths.[35–37]

The main components of the adaptive optics system are (1) A Hartmann-Shack wavefront sensor (microlens array 40 × 32, 3.6 mm effective diameter, centered at 1062 nm; HASO 32 OEM, Imagine Eyes), which measures the ocular aberrations; (2) A psychophysical channel (a slide with a sunburst chart located in a conjugate pupil plane, monochromatically back-illuminated with light coming from the super-continuum laser source and subtending 1.62 degrees on the retina), which allows projection of psychophysical stimuli. The luminance of the stimulus was 20 to 25 cd/m^2 in the spectral range tested psychophysically (450 to 700 nm) and therefore in the photopic region at all wavelengths (>10 cd/m^2). (3) A Badal system that corrects for defocus. (4) A pupil-monitoring channel. (5) An electromagnetic deformable mirror (52 actuators, 15 mm effective diameter, 50 μm stroke; Mirao, Imagine Eyes), which for the purposes of this study, was used only to correct the aberrations of the optical system. Patients were aligned to the system (using an x-y-z stage), using the line of sight as a reference. A 6 mm artificial pupil was placed in a conjugate pupil plane to ensure that the pupil diameter during the measurements did not exceed that value. All optoelectronic elements of the system (super-continuum laser source main source, Badal system, retinal image camera, pupil camera, Hartmann-Shack, and deformable mirror) are automatically controlled and synchronized, using custom-built software programmed in Visual C++ and C# (Microsoft Corp.). A dual acousto-optic modulator system, controlled with the software provided by the manufacturer, allowed automatic selection of the measurement wavelength. The custom-developed routines use the manufacturer's Software Development Kit for Hartmann-Shack centroiding detection and wave aberration polynomial fitting. Wave aberrations were fit by the 7th-order Zernike polynomials. The Optical Society of America convention was used for ordering and normalization of Zernike coefficients.[38] The longitudinal chromatic aberration of the system was measured, and measurements were corrected by the calibrated longitudinal chromatic aberration of the optical system, as described in detail in a previous publication.[20]

Experiments

The longitudinal chromatic aberration was obtained from psychophysical and objective estimates of best focus for each of the tested wavelengths. The best subjective focus was initially searched with the stimulus back-illuminated at a reference wavelength of 550 nm and set as zero. The following experiments were performed, in this order:

Experiment 1: Psychophysical Best Focus at Different Wavelengths Patients adjusted their best subjective focus using the Badal system while viewing the stimulus back-illuminated with different wavelengths in visible light (480 nm, 532 nm, 550 nm, 650 nm, and 700 nm). Patients were instructed to use the joystick to move the Badal toward the position where the stimulus, initially blurred by means of defocus induced with the Badal system, appeared sharp for the first time. Patients performed a trial before the experiment to become familiar with the test. The best focus settings were repeated 3 times for each wavelength, presented randomly.

Experiment 2: Hartmann-Shack Wave Aberrations at Different Wavelengths Wave aberrations were obtained in visible light (480 nm, 532 nm, 550 nm, 650 nm, and 700 nm) and near IR light (780 nm, 827 nm, and 950 nm), whereas the Badal system corrected the subjective defocus of the patient at 550 nm. The reference for best focus at 550 nm was obtained subjectively under natural aberrations for experiments 1 and 2.

Data Analysis

The best subjective foci at each wavelength in experiment 1 were directly obtained from the automatic readings of the Badal optometer. The best foci at each wavelength in experiment 2 were obtained from the 2nd-order Zernike defocus coefficients (C_2^0) in microns, from the Zernike polynomial expansions fitting the wave aberrations measured at each wavelength and using the expression $D = -16 . C_2^0 . \sqrt{3}/p^2$, where C_2^0 is the defocus Zernike coefficient in microns, p is the pupil diameter, and D is the defocus in diopters.

Chromatic difference of focus curves were obtained from the best foci versus wavelength dataset of each experiment. The longitudinal chromatic aberration was obtained from a 2nd-order polynomial fitting to those curves. The curves are shifted in the vertical axis such that they cross zero at 550 nm (the reference wavelength) for a unique reference for all techniques. For the psychophysical data, longitudinal chromatic aberration was computed for the visible range only. For the wavefront-sensing experiments, longitudinal chromatic aberration was computed for visible (480 to 700 nm), near IR (700 to 950 nm), and total spectral ranges (480 to 950 nm). For comparisons with the literature, the chromatic difference of focus between 2 specific wavelengths was also calculated.

Statistical analysis was performed with SPSS software (International Business Machines Corp.) to test differences in the estimated longitudinal chromatic aberration across experiments and conditions. A paired-samples *t* test was performed to analyze specific differences between conditions.

RESULTS

Wave Aberration Measurement at Different Wavelengths

Wave aberrations were measured for both eyes and all patients at 8 wavelengths. With wavelength, only the defocus Zernike term shows significant differences, whereas astigmatism and higher-order aberrations (HOAs) do not show systematic changes. Figure 1, *A* shows wave aberration maps (astigmatism and HOAs) in patient 6 for the eye implanted with the hydrophobic IOL (*upper row*) and hydrophilic IOL (*lower row*) IOLs, illustrating little variation in the wave aberrations with wavelength. On average across eyes, the variation of root mean square (RMS) for astigmatism and HOAs was less than 4% across wavelengths. Figure 1, *B* shows the average RMS (astigmatism and HOAs) across wavelengths for each patient (eyes with hydrophobic and hydrophilic IOLs, respectively). The RMS for astigmatism and HOAs was, on average, 0.48 ± 0.03 μm for the hydrophobic IOL and 0.39 ± 0.03 μm for the hydrophilic IOL (last bars in Figure 1, *B*).

Chromatic Difference of Focus From Psychophysical and Wavefront-Sensing

Figure 2 shows the measured chromatic difference of focus from psychophysical measurements (experiment 1: Figure 2, *A* for hydrophobic IOLs and (*B*) for hydrophilic IOLs) and from the defocus Zernike coefficients from wavefront-sensing (experiment 2: Figure 2 (*C*) for hydrophobic IOLs and (*D*) for hydrophilic IOLs) for all measured wavelengths in each experiment. Lines represent polynomial fitting curves to the data.

Longitudinal Chromatic Aberration: Differences Across Eyes and Techniques

Figure 3 shows longitudinal chromatic aberration from psychophysical measurements (*A*) in the visible range (480 to 700 nm), from wavefront-sensing (*B*) in the visible range (480 to 700 nm), and (*C*) in the total spectral range (480 to 950 nm) for all patients and all

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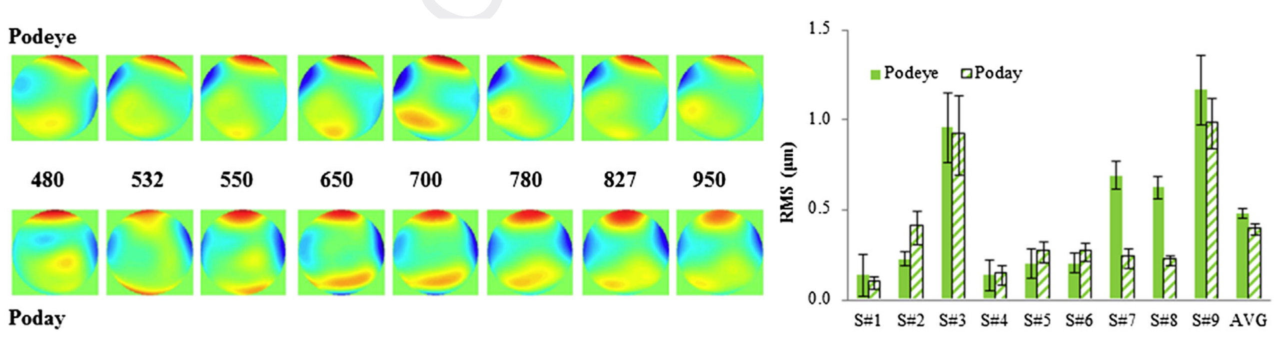

Figure 1. (*A*) Wave aberration maps for the astigmatism and HOAs in patient 6 for the eye implanted with the hydrophobic (*upper row*) and hydrophilic (*lower row*) IOLs, for all measured wavelengths. (*B*) Averaged RMS (astigmatism and HOAs) for all patients (eyes implanted with hydrophobic and hydrophilic IOLs, respectively), and average across each IOL type. Data are for 6.0 mm pupils.

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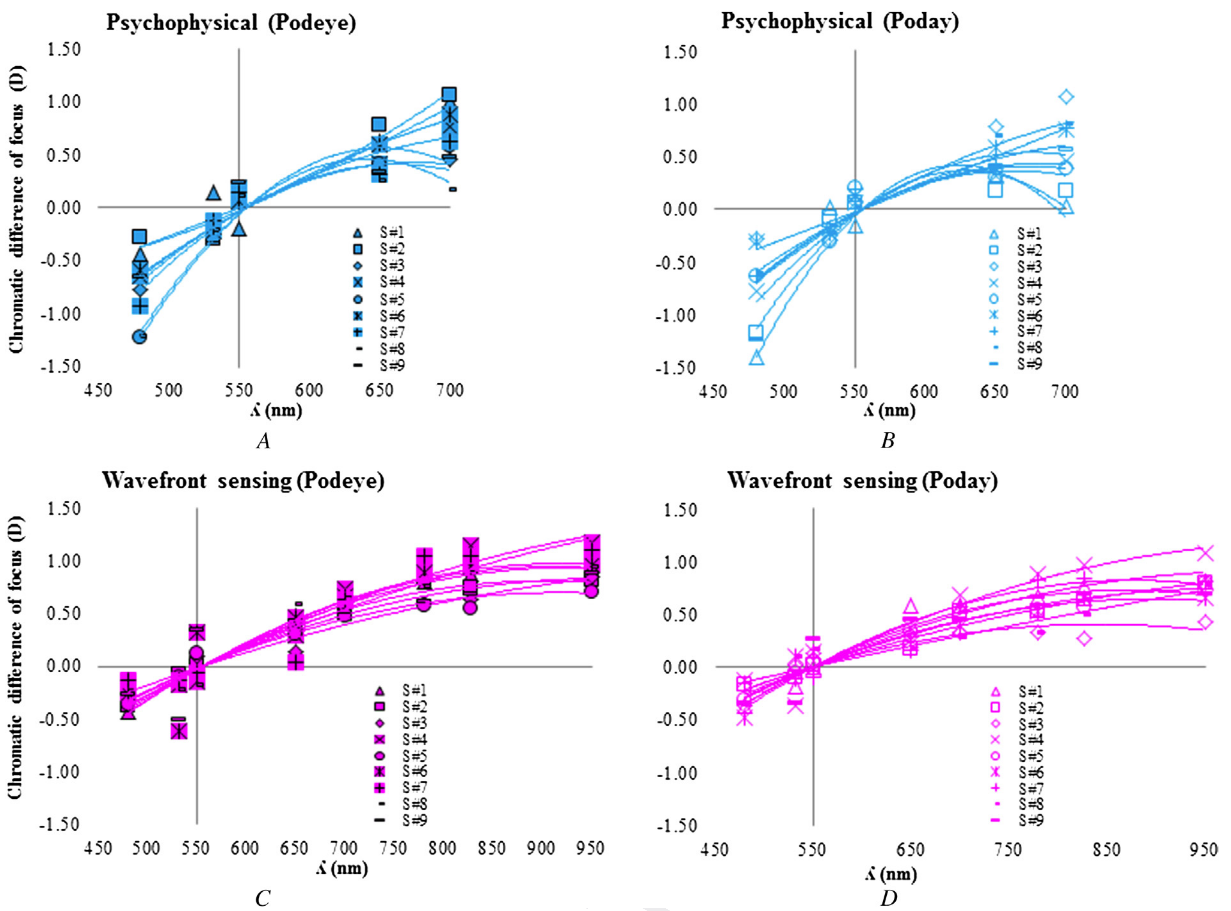

Figure 2. Chromatic difference of focus from psychophysical best focus of monochromatic stimuli (*A* and *B*) and from defocus Zernike terms from wavefront-sensing (*C* and *D*) for eyes implanted with the hydrophobic (*A* and *C*) and hydrophilic (*B* and *D*) IOLs, for all patients and all measured wavelengths (psychophysical: 480 nm, 532 nm, 550 nm, 650 nm, and 700 nm; wavefront-sensing: 480 nm, 532 nm, 550 nm, 650 nm, 700 nm, 780 nm, 827 nm, and 950 nm). Data are referred to the best focus at 550 nm, set as zero defocus.

implanted eyes, hydrophobic (*solid bars*) and hydrophilic (*dashed bars*).

Table 3 shows the average longitudinal chromatic aberration from psychophysical and wavefront-sensing measurements in the different spectral ranges measured for both IOL types. The longitudinal chromatic aberration from the hydrophobic IOL is statistically higher than the longitudinal chromatic

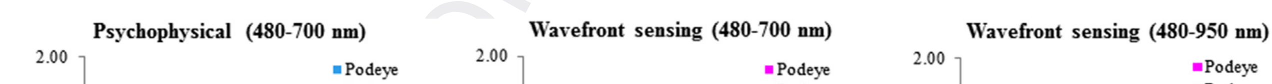

Figure 3. Longitudinal chromatic aberration from (*A*) subjective best focus and (*B*) wavefront-sensing for the visible (480 to 700 nm) and (*C*) visible + near IR (480 to 950 nm) spectral range for all patients and averaged across patients. Solid bars indicate eyes implanted with the hydrophobic IOL; dashed bars indicate eyes implanted with the hydrophilic IOL. Error bars in the subjective longitudinal chromatic aberration stand for standard deviation of repeated measurements.

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Table 3. Averaged LCA from psychophysical and wavefront-sensing measurements in the different spectral ranges measured for both IOL types and *P* values from paired-samples *t* test.

		Psychophysical			Wavefront-Sensing		
		Podeye	Poday	*P* Value	Podeye	Poday	*P* Value
Visible	480–700 nm	1.37 ± 0.08 D	1.21 ± 0.08 D	.003*	0.88 ± 0.07 D	0.73 ± 0.09 D	.004*
NIR	700–950 nm				0.39 ± 0.07 D	0.29 ± 0.08 D	.184
Visible + NIR	480–950 nm				1.27 ± 0.09 D	1.02 ± 0.13 D	.004*

aberration from the hydrophilic IOL in both techniques in the visible range as well as in the total spectral range. Intersubject variability is small for both techniques: ±0.008 D for the psychophysical technique (visible range) and ±0.006 D for wavefront-sensing (total spectral range).

DISCUSSION

We measured the longitudinal chromatic aberration in a wide range of wavelengths by using a psychophysical method and wavefront-sensing at multiple wavelengths—both implemented in the same polychromatic adaptive optics system—on pseudophakic eyes bilaterally implanted, 1 eye with the hydrophobic Podeye IOL and the contralateral eye with Poday the hydrophilic IOL. The study design minimizes potential patient bias, particularly in psychophysical measurements (same patient perform the subjective best focus settings with either IOL) as well as a direct comparison of both lower-order aberrations and HOAs across groups.

We found that the eyes implanted with the hydrophobic IOL exhibit a small but consistently higher longitudinal chromatic aberration than the eyes implanted with the hydrophilic IOL (a difference of 0.16 D and 0.15 D from psychophysical and wavefront-sensing methods, respectively, in the visible 480 to 700 nm range). The difference is consistent with the lower Abbe number of the hydrophobic material. The IOL material potentially has relevance on visual performance, as the IOL material affects the chromatic aberration of the eye.

We found that the longitudinal chromatic aberration from the psychophysical method is consistently higher (P = .001) for all eyes than the longitudinal chromatic aberration obtained from wavefront-sensing, by 0.48 D (35.41%) for the hydrophobic IOL and 0.48 D (39.43%) in the hydrophilic IOL. Similar differences were also found in a previous study[20] on young phakic eyes, using the same experimental system (0.61 D, 40.4%). Lower values of longitudinal chromatic aberration from reflectometric than from psychophysical had been also reported earlier. Some studies[1,7,39] had attributed those differences to the presence of HOAs, although our previous study[20] discarded this hypothesis by performing measurements under correction of natural aberrations with adaptive optics, which showed similar discrepancies between psychophysical and reflectometric (wavefront-sensing and double-pass–based) techniques. It is likely that the differences arise by wavelength-dependent reflectivity of the different retinal layers. In our previous study,[20] we showed that deviations in the best focus from psychophysical and reflectometric techniques occurred both at the short and long range of the spectrum, with higher shift in red than in blue light. We hypothesized that blue light was reflected anteriorly from the photoreceptors' inner segments, approximately in the retinal nerve fiber layer, and that red light was reflected behind the photoreceptors, in the choroid. This fact is interesting because in red light, the contribution of the choroidal reflections is large compared with that of reflections originating in the inner layers of the retina[40] and might explain the higher shift in red than in blue light. In any case, the relative difference in longitudinal chromatic aberration in eyes implanted with different IOLs remains constant regardless of the measurement technique.

The longitudinal chromatic aberration measured in the pseudophakic eyes of the current study can be compared with the longitudinal chromatic aberration measured in our previous study on young phakics, using the same methods,[20] and for similar wavelength ranges (Figure 4). For both techniques, we found that the longitudinal chromatic aberration in phakic eyes is higher than in the pseudophakic eyes. These differences were statistically significant with both techniques for the hydrophilic IOL, but only for the wavefront-sensing technique for the hydrophobic IOL (independent-samples t test): psychophysical: hydrophilic phakic, P = .002; wavefront-sensing: (1) visible, hydrophobic phakic, P = .041, hydrophilic phakic, P = .009; (2) near IR, hydrophilic phakic, P = .008; (3) visible + near IR, hydrophobic phakic, P = .018, hydrophilic phakic, P = .02. The longitudinal chromatic aberration in these pseudophakic eyes is, on average, similar than the longitudinal chromatic aberration in normal phakic eyes, whether measured

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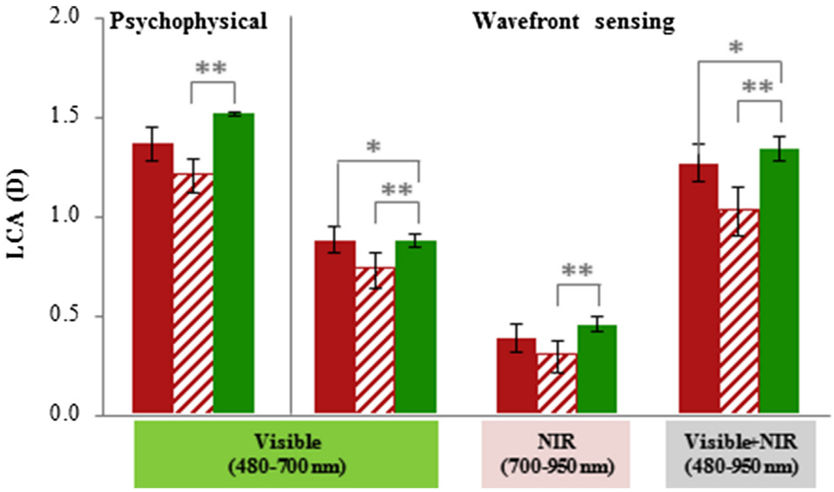

Figure 4. Longitudinal chromatic aberration averaged across patients for the hydrophobic IOL (*red solid bars*), hydrophilic IOL (*red dashed bars*), and phakic eyes (*green solid bars*) for spectral ranges in the visible, near IR, and total spectral ranges, from subjective best focus and wavefront-sensing. *, **Statistically significant ($P < .05$) and highly statistically significant ($P < .01$) differences, respectively, between pseudophakic and phakic eyes. Error bars stand for measurement error for subjective longitudinal chromatic aberration and intersubject variability in wavefront-sensing.

with the psychophysical or reflectometry technique, in the same spectral ranges.

Chromatic aberrations play a major role on the quality of vision[1,29,41,42]; however, only a few studies have addressed the chromatic properties of the IOLs and the chromatic aberration of the pseudophakic eyes in vivo. Our study provides estimates of the longitudinal chromatic aberration measured in a wider spectral range in the visible and near IR than that of previous studies, using psychophysical and wavefront-sensing measurements. Figure 5 shows the chromatic difference of focus found in the current study (psychophysical data in *blue*; wavefront-sensing, in *pink*), in comparison with in vivo chromatic difference of focus (in the corresponding spectral range) from previous studies from psychophysical (*red triangles*) and reflectometric (*green circles*) techniques with different types of IOLs.[27,33,34] In general, our results fall within values reported by previous studies that used both psychophysical and reflectometric techniques, with the data from psychophysical techniques showing consistently higher longitudinal chromatic aberrations than those from reflectometry techniques.

WHAT WAS KNOWN

- Chromatic aberrations play a major role on the quality of vision, and the longitudinal chromatic aberration has been extensively measured in phakic eyes. Most estimates of longitudinal chromatic aberration in pseudophakic eyes come from computations based on the IOL material Abbe number, and very few come from actual measurements on patients.

WHAT THIS PAPER ADDS

- There were significant but small differences in the longitudinal chromatic aberration with hydrophobic and hydrophilic IOLs, the longitudinal chromatic aberration being consistently smaller with hydrophilic IOLs. The longitudinal chromatic aberration from psychophysical measurements was consistently higher than those from wavefront-sensing, also in pseudophakic eyes.

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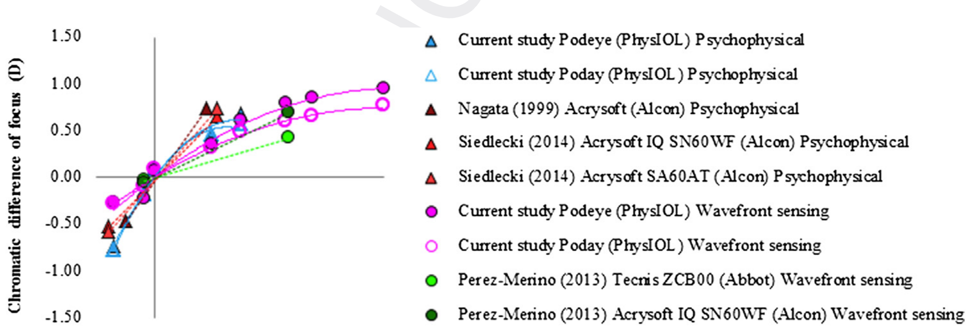

Figure 5. Chromatic difference of focus from the psychophysical (*blue triangles*) and wavefront-sensing (*pink circles*) measurements of the current study and other psychophysical (*red triangles*) and reflectometry (*green circles*) data in the literature. The measured chromatic range differed across studies, and it is indicated by the symbols in the end of the regression lines. Data are referred to zero defocus at 550 nm.

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