ARTICLE

In vivo subjective and objective longitudinal chromatic aberration after bilateral implantation of the same design of hydrophobic and hydrophilic intraocular lenses

Maria Vinas, MSc, Carlos Dorronsoro, PhD, Nuria Garzón, OD, MSc,
Francisco Poyales, MD, Susana Marcos, PhD

PURPOSE: To measure the longitudinal chromatic aberration in vivo using psychophysical and wavefront-sensing methods in patients with bilateral implantation of 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 (SD) (hydrophobic) and 1.21 $\pm$ 0.08 D (hydrophilic). From wavefront-sensing, the longitudinal chromatic aberration was 0.88 $\pm$ 0.07 D and 0.73 $\pm$ 0.09 D, respectively. At 480 to 950 nm, the longitudinal chromatic aberration was 1.27 $\pm$ 0.09 D (hydrophobic) and 1.02 $\pm$ 0.13 D (hydrophilic). The longitudinal chromatic aberration was consistently higher in eyes with the hydrophobic IOL than in eyes with the hydrophilic IOL (a difference of 0.16 D and 0.15 D, respectively). Similar to findings in young phakic eyes, the longitudinal chromatic aberration from the psychophysical method was consistently higher than from wavefront-sensing, by 0.48 D (35.41%) for the hydrophobic IOL and 0.48 D (39.43%) for the hydrophilic IOL.

CONCLUSION: Longitudinal chromatic aberrations were smaller with hydrophilic IOLs than with hydrophobic IOLs of the same design.

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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; this is 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, which is probably associated with differences in the measurement techniques, psychophysical[4,9–14] and reflectometric,[15–19] as well as the spectral range being tested. 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 lens 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 aimed at correcting the ocular longitudinal chromatic aberration.[29,30] The dispersion properties of the IOL are defined by the Abbe number (ranging in most 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] Few studies report in vivo measurements of longitudinal chromatic aberration in pseudophakic eyes. Nagata et al.[27] measured the longitudinal chromatic aberration in vivo (500 to 650 nm) in pseudophakic eyes 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 with 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 with 2 types of Acrysof IOLs (IQ SN60WF, spherical asymmetric biconvex IOL; SA60AT, aspheric asymmetric biconvex IOL; Alcon Laboratories, Inc.) 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 measured in vivo the longitudinal chromatic aberration in pseudophakic patients who had bilateral implantation of 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 Hartmann-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) (700 to 900 nm) ranges. Chromatic differences in focus curves

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From the Instituto de Óptica (Vinas, Dorronsoro, Marcos), Consejo Superior de Investigaciones Científicas, and the Instituto de Oftalmología Avanzada (Garzón, Poyales), Madrid, Spain.

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Corresponding author: Maria Vinas, MSc, Instituto de Óptica s, Consejo Superior de Investigaciones Científicas, Serrano 121, 28006, Madrid, Spain. E-mail: maria.vinas@io.cfmac.csic.es.

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 in young phakic patients performed using the same experimental system and with longitudinal chromatic aberration reported in 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 wavelengths in 9 patients who had bilateral implantation of an IOL of the same design but different material (hydrophobic Podeye and hydrophilic Poday, both PhysIOL). One eye of each patient was randomly assigned the hydrophobic IOL and the contralateral eye, the hydrophilic IOL. The time between the surgeries on the eyes of a patient was fewer than 7 days.

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 were approved by the Spanish National Research Council (Consejo Superior de Investigaciones Científicas) Bioethical Committee. All measurements were taken under mydriasis (tropicamide 1.0%, 2 drops 30 minutes before the beginning of the study and 1 drop every 1 hour).

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 IOL implantation, a clear capsule, and a postoperative CDVA better than 0.7.

Intraocular Lenses

The Podeye is a hydrophobic IOL, and the Poday is a hydrophilic IOL. Both IOLs are monofocal and aspheric but differ in their material. Table 1 shows the characteristics of the 2 IOL types.

Patient Assessments

Patients received a complete ophthalmic evaluation before enrollment in the study and before surgery at the Instituto de Oftamología Avanzada, Madrid, Spain. The preoperative examination included uncorrected (UDVA) and corrected (CDVA) distance visual acuities using the Early Treatment Diabetic Retinopathy Study (ETDRS) chart, biomicroscopy, corneal topography (Nidek Co., Ltd), tonometry (Goldmann), and a fundus evaluation. Axial length, anterior chamber depth, and white-to-white were measured with optical biometry (IOLMaster, Carl Zeiss Meditec AG). The IOL power was calculated with the Holladay 2 formula, targeting emmetropia.

Postoperative clinical evaluations were at 1 day, 1 week, and 1 month and included UDVA and CDVA using the ETDRS charts, 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 (Visiometrics S.L.). Night halos were measured using Halo software (version 1.0, University of Granada).

Surgical Technique

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

Polychromatic Adaptive Optics Setup

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

A supercontinuum laser source (SC400 femtopower 1060, Fianium Ltd.) was used as the light source of the system. This allowed 2 independently filtered light fiber outputs (visible channel: 480 nm, 532 nm, 550 nm, 650 nm, and 700 nm; 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 as follows: (1) A Hartmann-Shack wavefront sensor (microlens array 40 × 32, 3.6 mm effective diameter, centered at

Table 1. Specifications provided by the manufacturer.

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

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

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 candelas [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 6.0 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), while 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.

Statistical 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 so that they cross zero at 550 nm (the reference wavelength) for a unique reference for all techniques. For the psychophysical data, the longitudinal chromatic aberration was computed for the visible range only. For the wavefront-sensing experiments, longitudinal chromatic aberration was computed for the visible (480 to 700 nm), near IR (700 to 950 nm), and total spectral (480 to 950 nm) ranges. 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

Patients and Intraocular Lenses

Nine patients (mean age 73.92 years ± 4.28 [SD]) participated in the study. Table 2 shows the age, refractive, and clinical profiles of the participants.

Wave Aberration Measurement at Different Wavelengths

With wavelength, only the defocus Zernike term showed significant differences, whereas astigmatism and higher-order aberrations (HOAs) did not show systematic changes. Figure 1, *A*, shows wave aberration maps (astigmatism and HOAs) in patient 6 for the eye with the hydrophobic IOL and the eye with the hydrophilic IOL, showing little variation in the wave aberrations with wavelength. On average across eyes, the variation of the 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

Table 2. Optometric subjective refractions preoperatively and 1 month postoperatively.

			Preoperative Data				Follow-up (1 Month)			
Subject/Eye/Sex	IOL Implanted	IOL Power	Sph	Cyl	Axis	DCVA (LogMAR)	Sph	Cyl	Axis	DCVA (LogMAR)
S1/R/M	Hydrophobic	21.50	3	−1	80	0.4	1.5	−1.25	80	0
S1/L	Hydrophilic	22.50	4	−0.5	90	0.3	0	0	0	0
S2/R/F	Hydrophilic	20.50	−0.75	−1	90	0.15	0	0	0	0
S2/L	Hydrophobic	21.00	−1.75	−1.25	95	0.2	0	0	0	0.05
S3/R/F	Hydrophobic	21.00	1.75	−1	55	0.3	0	−0.75	80	0
S3/L	Hydrophilic	19.50	1.25	−1	115	0.2	0	−0.75	100	0
S4/R/M	Hydrophilic	18.50	1.25	1.25	180	0.1	−1	0	0	0
S4/L	Hydrophobic	18.00	0.75	−0.5	12	0.2	0	0	0	0
S5/R/F	Hydrophilic	21.00	1.75	−1	90	0.2	0	0	0	0
S5/L	Hydrophobic	20.50	1.25	−0.5	65	0.25	0	0	0	0
S6/R/M	Hydrophobic	23.00	−2.75	−0.75	120	0.3	0	0	0	0
S6/L	Hydrophilic	22.50	−3.25	−1	110	0.25	0	0	0	0
S7/R/F	Hydrophobic	20.00	−1	−2.25	20	0.5	1	−1	180	0
S7/L	Hydrophilic	21.50	0.5	−0.5	180	0.3	0	0	0	0
S8/R/F	Hydrophobic	18.00	−2.75	−1.5	105	0.2	0.5	−1.5	95	0
S8/L	Hydrophilic	19.50	0	−1	70	0.1	0.5	−1	75	0
S9/R/F	Hydrophilic	19.00	−1	−0.5	70	0.2	0	−0.75	100	0
S9/L	Hydrophobic	18.00	−1	−0.75	100	0.25	0.75	−0.5	70	0

Cyl = cylinder; DCVA = distance-corrected visual acuity; IOL = intraocular lens; Sph = spherical error

average, 0.48 ± 0.03 μm for the hydrophobic IOL and 0.39 ± 0.03 μm for the hydrophilic IOL.

Chromatic Difference of Focus From Psychophysical and Wavefront-Sensing

Figure 2 shows the measured chromatic difference of focus from psychophysical measurements (experiment 1) and from the defocus Zernike coefficients from wavefront-sensing (experiment 2) 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 the longitudinal chromatic aberration from psychophysical measurements in the visible range (480 to 700 nm), from wavefront-sensing in the visible range (480 to 700 nm), and in the total spectral range (480 to 950 nm) in all patients and all eyes.

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

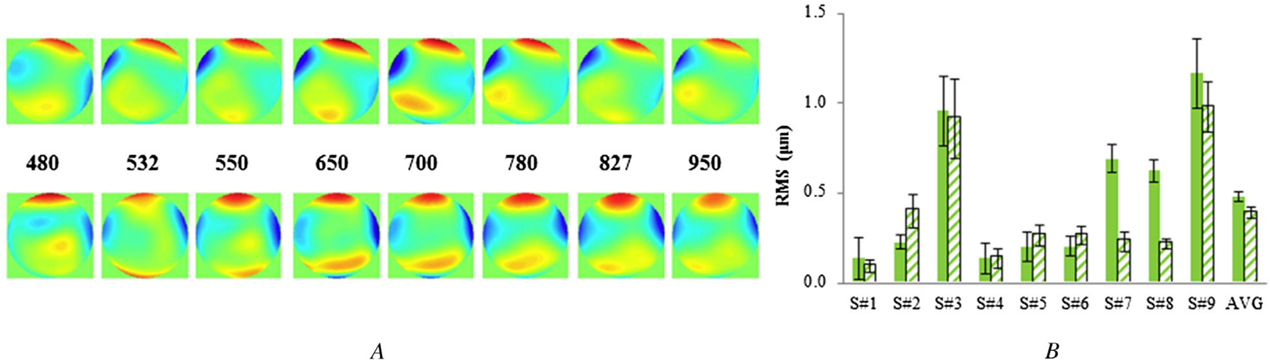

Figure 1. (*A*) Wave aberration maps for the astigmatism and HOAs in patient 6 in the eye with the hydrophobic IOL (*upper row*) and the eye with the hydrophilic IOL (*lower row*) IOLs, for all measured wavelengths. (*B*) Averaged RMS (astigmatism and HOAs) for all patients (eyes implanted with hydrophobic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

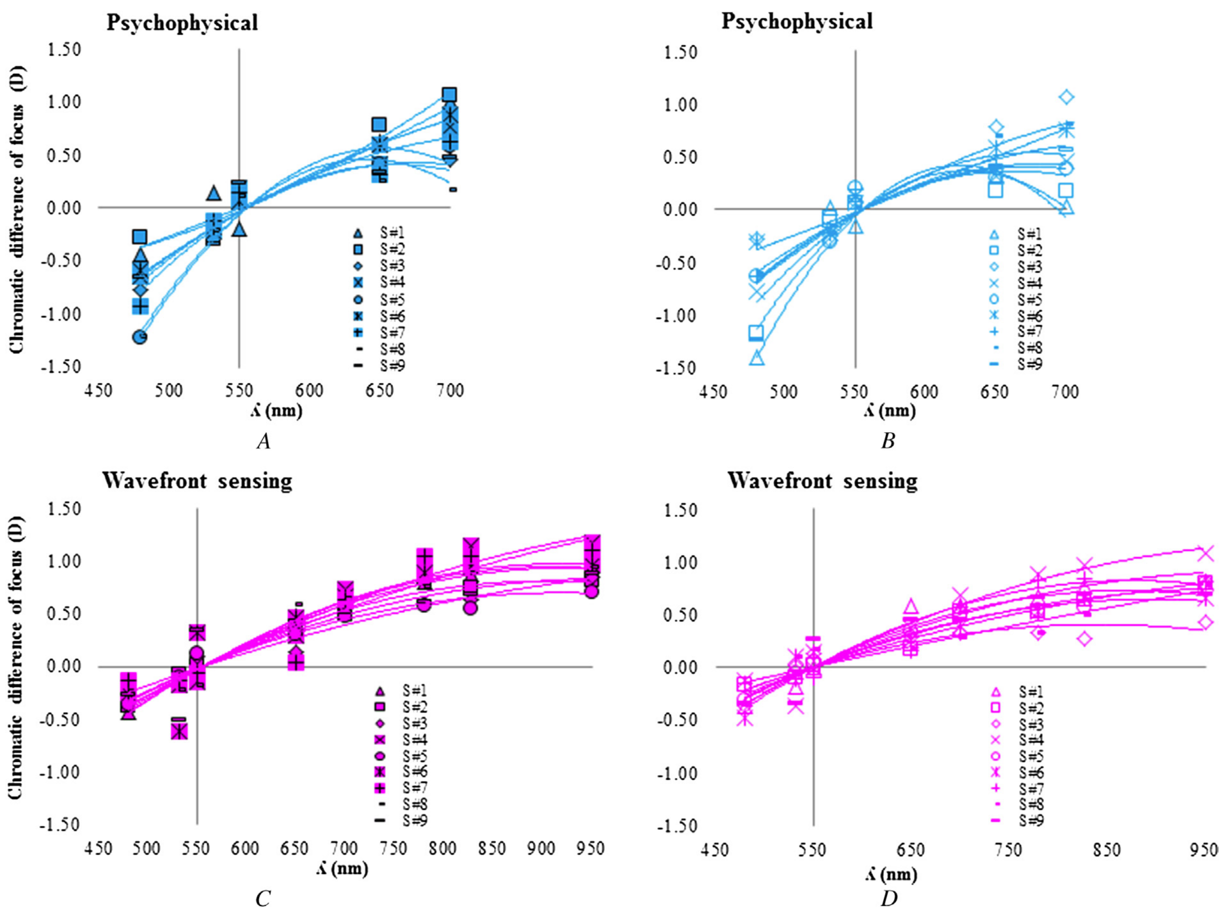

Figure 2. Chromatic difference of focus from psychophysical best focus of monochromatic stimuli (*A* and *B*) and from defocus Zernike terms from wavefront-sensing (*C* and *D*) for eyes with the hydrophobic IOL (*A* and *C*) and hydrophilic IOL (*B* and *D*), in all patients and all measured wavelengths (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.

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

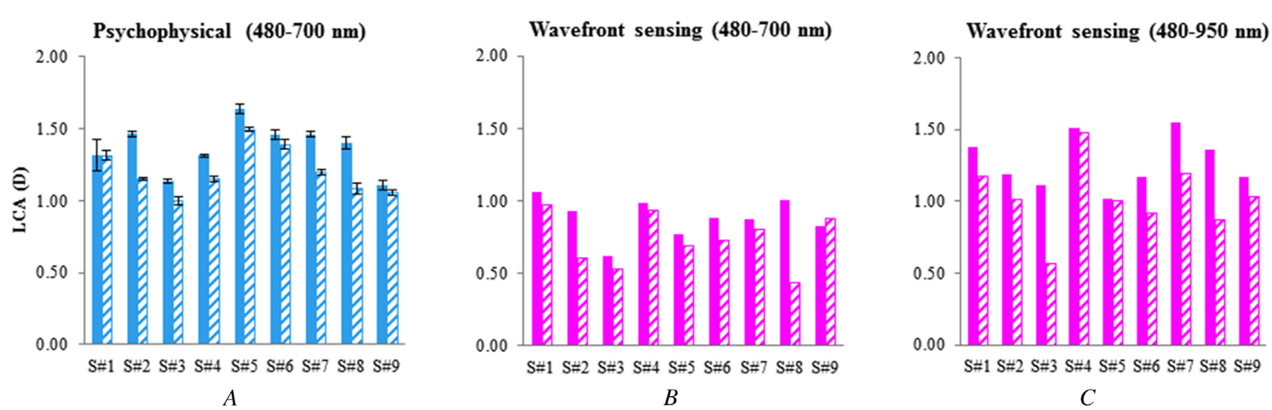

Figure 3. Longitudinal chromatic aberration from (*A*) subjective best focus and (*B*) wavefront-sensing for the visible (480 to 700 nm) and (*C*) visible + near IR (480 to 950 nm) spectral range in all patients and averaged across patients. Solid bars indicate eyes with the hydrophobic IOL; dashed bars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

Table 3. Mean longitudinal chromatic aberrations from psychophysical and wavefront-sensing measurements in the different spectral ranges.

		Psychophysical			Wavefront-Sensing		
Light	Range (nm)	Hydrophobic IOL	Hydrophilic IOL	*P* Value*	Hydrophobic IOL	Hydrophilic IOL	*P* Value*
Visible	480–700	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				0.39 ± 0.07 D	0.29 ± 0.08 D	.184
Visible + NIR	480–950				1.27 ± 0.09 D	1.02 ± 0.13 D	.004†

IOL = intraocular lens; NIR = near infrared
*Paired-samples *t* test
†Statisically significant difference ($P < .05$)

DISCUSSION

We measured the longitudinal chromatic aberration in a wide range of wavelengths using a psychophysical method and wavefront-sensing at multiple wavelengths—both implemented in the same polychromatic adaptive optics system—in pseudophakic eyes of the same patient, 1 eye with the hydrophobic Podeye IOL and the contralateral eye with the Poday hydrophilic IOL. The study design minimizes potential patient bias, particularly in psychophysical measurements (same patient performs 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 with the hydrophobic IOL had a small but consistently higher longitudinal chromatic aberration than eyes 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 regarding visual performance as the IOL material affects the chromatic aberration in the eye.

The longitudinal chromatic aberration from the psychophysical method was consistently higher ($P = .001$) in 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%) for the hydrophilic IOL. Similar differences were also found in a previous study[20] of young phakic eyes using the same experimental system (0.61 D, 40.4%). Lower values of longitudinal chromatic aberration from the reflectometric than from psychophysical method had also been reported earlier. Some studies[1,7,39] 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 a higher shift in red light 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 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 light than in blue light. In any case, the relative difference in longitudinal chromatic aberration in eyes with different IOLs remains constant regardless of the measurement technique.

The longitudinal chromatic aberration measured in the pseudophakic eyes in the current study can be compared with the longitudinal chromatic aberration measured in our previous study of 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 the phakic eyes was 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 was, on average, similar to

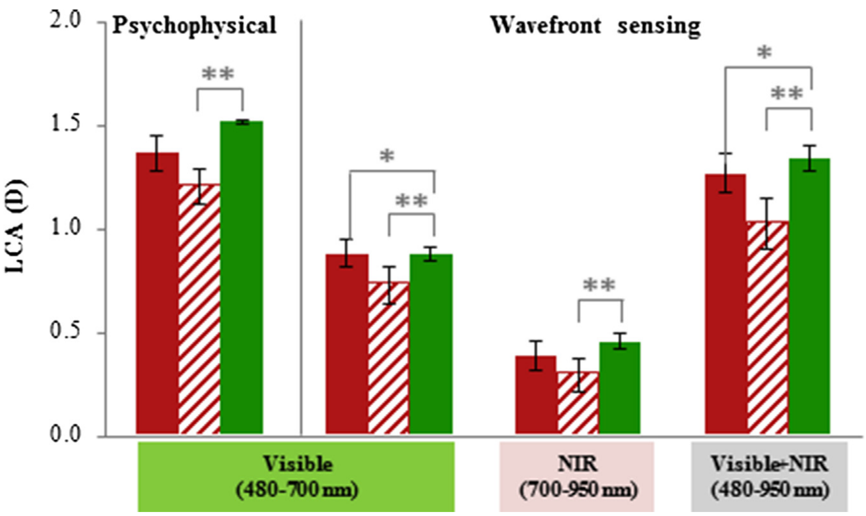

Figure 4. Longitudinal chromatic aberration averaged across patients for the hydrophobic IOL (*red solid bars*), hydrophilic IOL (*red dashed bars*), and phakic eyes (*green solid bars*) for spectral ranges in the visible, near IR, and total spectral ranges, from subjective best focus and wavefront-sensing.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

the longitudinal chromatic aberration in normal phakic eyes, whether measured with the psychophysical or reflectometry technique, in the same spectral ranges.

Chromatic aberrations play a major role in the quality of vision[1,29,41,42]; however, 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 in previous studies, using psychophysical and wavefront-sensing measurements. Figure 5 shows the chromatic difference of focus found in the current study in comparison with in vivo chromatic difference of focus in the corresponding spectral range from previous studies of psychophysical and reflectometric techniques with different types of IOLs.[27,33,34] In general, our results fall within the values reported in 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 in 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 in 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.

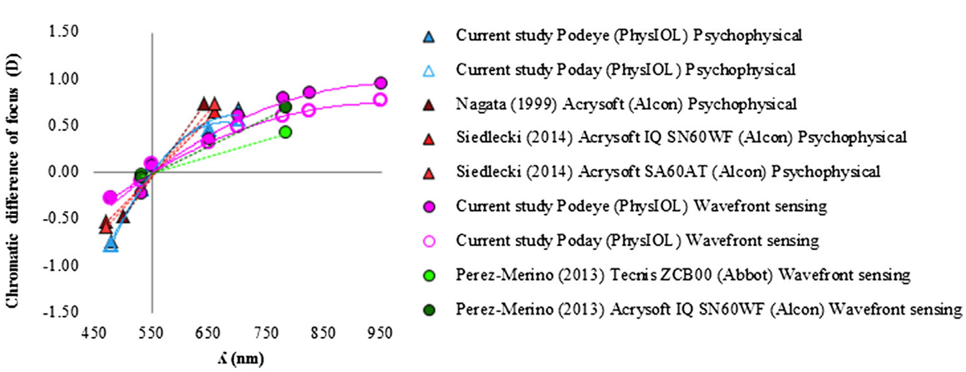

Figure 5. Chromatic difference of focus from the psychophysical (*blue triangles*) and wavefront-sensing (*pink circles*) measurements in the current study and other psychophysical (*red triangles*) and reflectometry (*green circles*) data in the literature. The measured chromatic range differed across 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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