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Young eyes for elderly people

Gaalen, Kim Warda van

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Comparison of the optical performance of eyes with aspheric foldable intraocular lenses, spherical foldable lenses and rigid PMMA lenses

Higher-order aberrations, contrast sensitivity, depth of focus, myopic shift and straylight

Kim W. van Gaalen[1], MSc, Nomdo M. Jansonius[1,2], MD, PhD,
Steven A. Koopmans[2], MD, PhD and Aart C. Kooijman[1], PhD

[1] Laboratory of Experimental Ophthalmology, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands
[2] Department of Ophthalmology, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands

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Abstract

Purpose

To compare the optical performance of rigid spherical PMMA intraocular lenses (IOLs), foldable spherical IOLs and foldable aspheric IOLs.

Methods

Measurements were obtained monocularly from pseudophakic patients with a PMMA IOL (Ophtec PC265Y or Rayner 105U), the spherical Acrysof MA30 IOL or the aspheric Tecnis ZA9003 IOL. Contrast sensitivity was measured using the Holladay automated contrast sensitivity test with a 5.0 mm artificial pupil at 3 and 6 cycles per degree, at optimal focus and at several defocus levels. The myopic shift (shift of the optimal focus toward more myopic values at lower spatial frequencies) and depth of focus were determined. Wavefront aberrations were assessed with a Hartmann-Shack wavefront analyzer; straylight was measured using the C-Quant.

Results

Nine patients with a spherical rigid PMMA IOL, 19 patients with a spherical foldable IOL and 24 patients with an aspheric foldable IOL were included. Eyes with an aspheric IOL showed less spherical aberration than eyes with other IOLs; no differences were found in the overall higher-order aberrations. No differences in contrast sensitivity at optimal focus and in straylight could be found among the IOLs. Eyes with a PMMA IOL showed a larger depth of focus compared to eyes with an aspheric IOL; eyes with an aspheric IOL had a smaller myopic shift than eyes with other IOLs.

Conclusions

Optical performance differences among the IOLs are small, concurring with the similar higher-order aberrations found in the three groups. Reduction in myopic shift seems to be aspheric IOLs' most obvious effect.

Introduction

The first intraocular lens (IOL) was made of PMMA, inspired by the inertia this material had when found in pilot's eyes containing fragments of shattered cockpit canopies, and it was implanted by Sir Harold Ridley in November 1949.[1] In 1962, Charles Kelman introduced the phacoemulsification technique. In this technique, the crystalline lens is shattered with ultrasound waves and removed through a small incision of approximately 3.0 mm, decreasing the amount of surgically induced astigmatism[2,3] and surgical trauma. This surgical development initiated the development of foldable IOLs, since the use of IOLs made of plexiglass (poly methyl metacrylate; PMMA) required a much larger incision of typically 6.0 mm. Foldable IOLs are made of either silicone or acrylate.

Initially, IOLs had spherical surfaces, increasing the positive spherical aberration of the pseudophakic optical system.[4,5] In phakic eyes, the spherical aberration is a combination of the positive spherical aberration of the cornea,[6,7] which is more or less constant throughout life,[7] and the negative spherical aberration of the crystalline lens.[8,9] When the crystalline lens ages, accommodation and the equivalent refractive index of the lens decreases,[8,10,11] and the curvature and thickness of the lens change.[11] As a consequence, the negative spherical aberration of the crystalline lens gradually changes into a positive spherical aberration and, hence, the overall spherical aberration of the human eye optics becomes positive.[6,12,13] Studies performed with healthy phakic eyes have shown an age-related increase in spherical aberration,[12-15] and a – presumably related[14] - decline in optical performance.[6,16-18]

To decrease spherical aberration after cataract surgery, an aspheric IOL with optical properties resembling those of a clear young human lens was designed.[19] The aspheric IOL has proven to reduce the spherical aberration of the human eye optics effectively.[20-34] In recent years, many studies have compared the optical performance of spherical foldable IOLs with that of aspheric foldable IOLs.[20-27,30-34] However, a non-negligible number of these studies have failed to demonstrate the expected increase in optical performance.[22,25,26,34]

The aim of the current study was to explore the optical performance of the pseudophakic eye throughout the recent history of IOL development. For this purpose, we measured visual acuity, contrast sensitivity at optimal focus, contrast sensitivity with defocus (to assess depth of focus and the myopic shift [shift of optimal focus towards more myopic values at lower spatial frequencies]), wavefront aberrations and straylight in three groups of patients: patients with a rigid PMMA IOL, patients with a foldable spherical IOL and patients with a foldable aspheric IOL.

Methods

Subjects

Measurements were performed monocularly in pseudophakic patients with either a spherical rigid PMMA IOL (PC265Y, Ophtec, Groningen, The Netherlands, n=11; 105U, Rayner, Hove, East Sussex, UK, n=3), a spherical foldable IOL (Acrysof MA30 [MA30BA, n=17; MA30BM, n=7], Alcon Labs, Forth Worth, TX, USA) or an aspheric foldable IOL (Tecnis ZA9003, AMO, Santa Ana, CA, USA, n=31). Table 1 shows the optical properties of the IOLs. All the cataract surgeries were performed in the University Medical Center Groningen, The Netherlands, using phacoemulsification at the 12:00 o'clock position through a 3.0 mm clear corneal incision (foldable IOLs) or 6.0 mm corneoscleral incision (PMMA IOLs). This study was approved by the UMCG Medical Ethical Committee. Informed consent was obtained from all patients in accordance to the tenets of the Declaration of Helsinki.

Posterior capsule opacification (PCO) was not allowed to be present in a central region (centered within the capsulorhexis) with a diameter of 3.0 mm. This was evaluated with a slitlamp by an experienced ophthalmologist. Further exclusion criteria included uveitis, retinal and optic nerve pathology such as macular degeneration, diabetic retinopathy or glaucoma, corneal opacities and irregularities, amblyopia and complications during cataract surgery, in short, any concurrent disease that might influence the optical or neural performance of the eye. Eyes with a refractive error of more than +/- 2 D spherical equivalent after cataract extraction were also excluded, as were patients with an astigmatism of more than 2.5 D. Eyes that had undergone neodymium:YAG laser capsulotomy treatment for PCO (PC265Y, n=5; 105U, n=1; MA30BA, n=5; MA30BM, n=1; ZA9003, n=0) were not excluded from the study. If both eyes met the inclusion criteria, the dominant eye was chosen. Best-corrected visual acuity was determined with an Early Treatment Diabetic Retinopathy Study (ETDRS) chart and had to be at least 20/25.

Straylight measurements

Straylight measurements were performed with the C-Quant (Oculus, Wetzlar, Germany) with a natural pupil size. This measurement is based on compensation comparison and has been described by Franssen and colleagues in detail.[35]

Table 1. *Optical and haptic characteristics of the IOLs implanted in this study.*

	Tecnis ZA9003	PC265Y	Rayner 105U	MA30BA	MA30BM
Optical					
Diameter (mm)	6.0	6.0	5.0	5.5	5.5
Shape	Equi-biconvex, modified prolate anterior surface	Biconvex	Biconvex	Biconvex	Biconvex
Material	UV-blocking hydrophobic acrylic	UV Blocking PMMA	UV Blocking PMMA	Acrylate/Methacrylate UV absorbing	Acrylate/Methacrylate UV absorbing
Surface	Aspheric	Spherical	Spherical	Spherical	Spherical
Estimated a-constant	119.1	118.0	118.7	118.9	118.9
Refractive index	1.46	1.49	1.49	1.55	1.55
Haptical					
Material	Polyvinylidene fluoride	PMMA	PMMA	PMMA	PMMA
IOL-type	3 piece	1 piece	3 piece	3 piece	3 piece
Length (mm)	12.0	12.0	13.75	12.5	12.5

Wavefront-aberration measurements

Wavefront aberrations of the whole eye were measured with a wavefront analyzer (WASCA version 1.26.3; Asclepion Meditec, Jena, Germany) and presented in standardized Optical Society of America (OSA) values.[36] The aberration coefficient c_4^0 belonging to the Zernike polynomial Z_4^0 was used as a measure of spherical aberration; the root of the sum of the squares of all coefficients from the 3rd order up to the 6th order was used as a measure of higher-order aberrations. Wavefront aberrations were measured between 30 min and 1 hour after administration of two drops of tropicamide 0.5% and two drops of phenylephrine 2.5% (Chauvin Pharmaceuticals Ltd, Kingston-upon-Thames, Surrey, UK) and were calculated for a 5.0 mm apparent pupil (which is about 12% larger than the physical pupil size[37] as used in the WASCA software). The results of the wavefront aberration measurements were not available during the contrast sensitivity testing.

Contrast-sensitivity measurements

Contrast sensitivity tests were performed between 30 minutes and 3 hours after the administration of two drops of tropicamide 0.5% and two drops of phenylephrine 2.5% (Chauvin Pharmaceuticals Ltd, Kingston-upon-Thames, Surrey, UK) under photopic conditions (85 cd/m^2) with an artificial pupil of 5.0 mm in a trial frame. Contrast sensitivity was tested using the Holladay automated contrast sensitivity test (HACSS; M&S Technologies, Skokie, IL, USA) at two spatial frequencies, 3 and 6 cycles per degree (cpd). For details of this test, see Van Gaalen et al.[14] To summarize, the test begins with 50% contrast, at 6 cpd. The subject has to indicate whether the displayed stimulus is a circular pattern or a blank disk. After each correct answer, the contrast of the stimulus decreases 0.3 log units. When an incorrect answer is given, contrast increases 0.3 log units (after the second incorrect answer, 0.2 log units) and then decreases again, but this time in steps of 0.1 log units until the next incorrect response. Throughout the test, several blank disks are shown at the same mean luminance level so as to check reliability. The contrast threshold corresponds to the lowest contrast level at which the subject identifies two of three circular patterns correctly. Contrast sensitivity is the reciprocal of this contrast threshold and is based on Michelson contrast:

$$\text{Michelson Contrast} = \frac{L_{\max} - L_{\min}}{L_{\max} + L_{min}} \qquad (1)$$

where L_{max} is the maximum luminance of the bright circles and L_{min} the minimum luminance of the dark circles. Contrast sensitivity was measured with optimal refraction for the viewing distance and at several levels of defocus: -2 D, -1 D and +1 D. The test was performed at the advised viewing distance of 4 m.

Myopic shift and the depth of focus

Spherical aberration causes a shift of the optimum focus at low spatial frequencies, rendering the eye more myopic.[38] The size of this myopic shift and the depth of focus can be used to estimate the amount of spherical aberration and higher-order aberrations together, respectively.[38,39] In the present study, the myopic shift and depth of focus of the eye were determined by fitting a parabola through the log contrast sensitivity as a function of the defocus curve at 6 cpd. To increase accuracy, we required the R^2 of the fitted parabola to be at least 0.85 and the highest contrast sensitivity value was not allowed to correspond to one of the two extreme defocus values (-2 D and +1 D). The myopic shift was defined as the dioptric difference between the top of the fitted parabola and the 0 D defocus level; 0 D corresponds to the optimal refraction as determined using small optotypes (Figure 1, *A*). Depth of focus was defined as the dioptric range for which contrast sensitivity exceeds half of its maximum value (full width at half height, that is, the width as measured 0.3 log below the peak; Figure 1, *B*).[40]

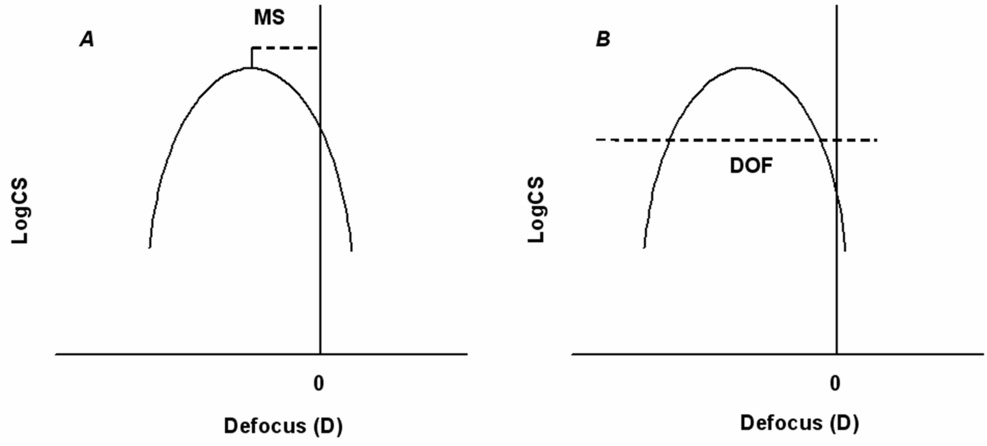

Figure 1. *Illustration of the definitions of myopic shift (**A**) and depth of focus (**B**) applied in this study. For details see text (LogCS = log contrast sensitivity; MS = myopic shift; DOF = depth of focus).*

Statistical analysis

The main outcome variable of the contrast sensitivity test was the logarithmic value of contrast sensitivity (logCS). ANOVA (GLM) for repeated measurements with post-hoc analysis (one-way ANOVA) with Bonferroni correction was performed in order to identify effects within the log contrast sensitivity values of the various levels of defocus and among the IOL types. One-way ANOVA with Bonferroni correction was used to analyze differences in wavefront aberrations, and one-way ANOVA with post-hoc analysis (t-test for independent samples) was used to analyze differences in visual acuity, depth of focus, myopic shift and straylight among the IOLs. To obtain reliable straylight values, straylight parameter log(s) had to be less than 2.5 in both eyes with a standard deviation of less than 0.12.[41-43] A *P*-value of 0.05 or less was considered statistically significant.

Results

A total of 9 patients with a spherical rigid PMMA IOL (PC256y, n = 7; 105U, n = 2), 19 patients with a spherical foldable IOL (MA30BA, n = 13; MA30BM, n = 6) and 24 patients with an aspheric foldable IOL (Tecnis ZA9003) met the inclusion criteria regarding the quality of the contrast sensitivity data (see Methods) and were included in the analyses. The average follow-up duration was 10.7 years (range 9.1 to 13.6 years) for the ridged PMMA IOLs, 5.9 years (range 1.6 to 10.5 years) for the spherical foldable IOLs and 0.2 years (range 0.1 to 0.4 years) for the aspheric foldable IOLs. The mean age in the PMMA group was 69.4 years (standard deviation 7.2, range 55 to 81 years), in the MA30 group 68.3 years (standard deviation 10.3, range 48 to 83 years) and in the Tecnis group 69.8 years (standard deviation 11.0, range 45 to 87 years). The mean age did not differ significantly among the IOL groups. Furthermore, the postoperative refractive error did not differ statistically significant among the groups.

Table 2 shows the visual performance of the three groups: visual acuity, straylight, and contrast sensitivity measured at 3 cpd and 6 cpd at optimal focus. Table 3 presents the spherical aberration and the higher-order aberration values with and without spherical aberration included, for each group.

Table 2. *Visual performance of pseudophakic eyes with the ridgid PMMA IOL, the spherical foldable IOL and the aspheric foldable IOL (mean +/- standard deviation with range between brackets).*

		Visual acuity (VAR)	Contrast sensitivity (LogCS)		Straylight (Log)
			3 cpd	6 cpd	
PMMA PC265y/105U	(n = 9)	99.4 ± 3.0	1.54 ± 0.18	1.56 ± 0.26	1.26 ± 0.25
Acrysof MA30	(n =19)	100.9 ± 4.4	1.51 ± 0.21	1.63 ± 0.19	1.35 ± 0.19
Tecnis ZA9003	(n = 24)	101.0 ± 3.6	1.58 ± 0.16	1.68 ± 0.28	1.38 ± 0.26
P-value		.544	.514	.475	.467

VAR = visual acuity rate; LogCS = log contrast sensitivity; cpd = cycles per degree.

Table 3. *Wavefront data in patients with a PMMA IOL, a MA30 or a Tecnis ZA9003 (mean +/- standard deviation with range between brackets).*

IOL type		C_4^0 (µm)	$\lvert C_4^0 \rvert$ (µm)	HOA (µm)	HOA excluding C_4^0 (µm)
PMMA	(n = 9)	0.11 ± 0.07	0.11 ± 0.07	0.27 ± 0.07	0.24 ± 0.06
MA30	(n = 19)	0.11 ± 0.04	0.11 ± 0.04	0.29 ± 0.09	0.26 ± 0.10
Tecnis ZA9003	(n = 24)	-0.04 ± 0.05	0.05 ± 0.04	0.24 ± 0.07	0.23 ± 0.07
P-value		< .001	< .001	.158	.498

HOA = root of sum of squares of the wavefront aberration coefficients from the 3rd up to the 6th order Zernike polynomials.

No difference in visual acuity, straylight and in any of the wavefront aberration coefficients could be found, except for the aberration coefficient c_4^0; eyes with the Tecnis IOL (-0.04 ± 0.05 µm) had a significantly lower spherical aberration than eyes with the PMMA IOL (0.11 ± 0.07 µm; $P < .001$) and the MA30 IOL (0.11 ± 0.04 µm; $P < .001$). The higher-order aberrations with and without the spherical aberration term (c_4^0) included did not differ statistically significantly between the three IOL groups. This indicates that the contribution of the spherical aberration to the higher-order aberrations was limited.

No differences in contrast sensitivity at optimal focus among the IOLs could be measured, neither at 3 cpd nor at 6 cpd. Figure 2 shows the through-focus curves measured at 6 cpd. No difference between eyes with the spherical IOLs (PMMA and MA30) could be found. Eyes with the Tecnis IOL, however, showed a significantly lower contrast sensitivity when -2 D defocus was applied (*P* = .002 when compared to eyes with the PMMA IOL and *P* = .001 when compared to eyes with the MA30 IOL). A similar difference was found at 3 cpd for the Tecnis IOL versus the MA30 IOL (*P* = .002), but not for the Tecnis IOL versus the PMMA IOL (*P* = .450).

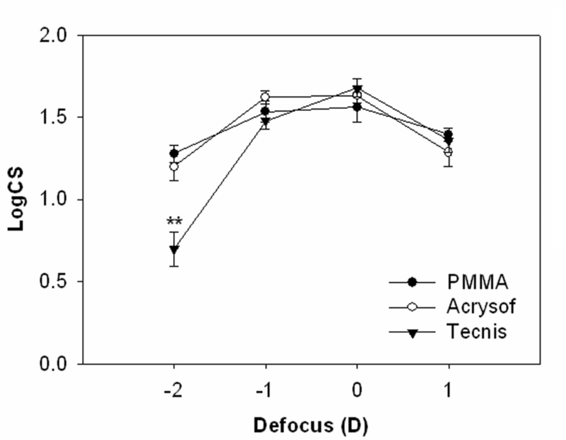

Figure 2. *Log contrast sensitivity (LogCS) as a function of defocus when measured at 6 cpd (mean +/- standard error of the mean, artificial pupil size = 5.0 mm; **Tecnis versus PMMA, P = .002; Tecnis versus MA30, P = .001).*

Figure 3 shows the myopic shift for the three IOL groups. The myopic shift of eyes with the Tecnis IOL (-0.03 ± 0.41 D; range -0.85 to 0.92 D) was significantly smaller than that of eyes with the MA30 IOL (-0.39 ± 0.35 D; range -1.12 to 0.34 D; *P* = .004) and of eyes with the PMMA IOL (-0.35 ± 0.21; range -0.70 to -0.13 D; *P* = .033).

Figure 4 presents the depth of focus for the three IOL groups. The depth of focus of eyes with the PMMA IOL (3.16 ± 0.68 D; range 2.72 to 4.90 D) was statistically significantly larger than that of eyes with the Tecnis IOL (2.34 ± 0.65 D; range 1.20 to 3.70 D; *P* = .003), but not significantly different when compared to eyes with the MA30 IOL (2.70 ± 0.65 D; range 1.71 to 4.38 D; *P* = .094). The depth of focus of eyes with the MA30 IOL did not differ significantly from that of eyes with the Tecnis IOL (*P* = .078).

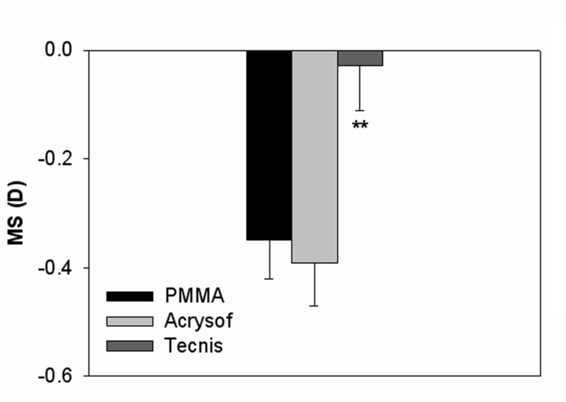

Figure 3. *Myopic shift (MS) measured for the three IOL groups (mean +/- standard error of the mean, artificial pupil size = 5.0 mm; **Tecnis IOL versus PMMA IOL P = .033, Tecnis IOL versus MA30 IOL P = .004).*

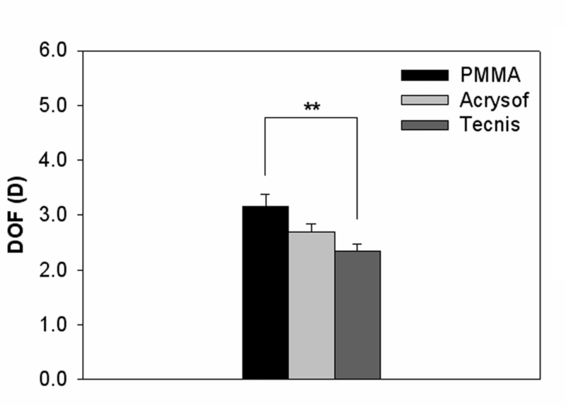

Figure 4. *Depth of focus (DOF) measured for the three IOL groups (mean +/- standard error of the mean, artificial pupil size = 5.0 mm; ** P = .003).*

Discussion

This study investigated the monochromatic higher-order aberrations and the optical performance of eyes with various IOLs: spherical rigid PMMA IOLs, spherical foldable IOLs and an aspheric foldable IOL. No differences in visual acuity, straylight and contrast sensitivity at optimal focus among the IOLs could be found. Eyes with a spherical IOL had significantly more spherical aberration when compared to eyes with the aspheric Tecnis IOL, and, related to that finding, eyes with the Tecnis IOL showed less myopic shift.

It should be pointed out that the follow-up period differed between the IOL groups – a consequence of the fact that PMMA IOLs are largely replaced by foldable IOLs in clinical practice, and aspheric IOLs were introduced only recently. This could have caused differences in optical performance due to differences in clarity of the posterior lens capsule. However, because the best-corrected visual acuity was required to be at least 20/25 and no PCO in the center of the capsulorhexis was allowed to be present, we expect no confounding by follow-up period. Moreover, no differences in straylight were found, an important marker of both PCO and cornea edema.

In the last few decades, the optical quality of pseudophakic eyes has received significant attention. Several studies have explored the difference in contrast sensitivity between spherical rigid PMMA IOLs and spherical foldable IOLs. For example, Johansen and colleagues[44] compared the contrast sensitivity at several spatial frequencies in 200 pseudophakic eyes with either a rigid PMMA IOL (PC44NB, Allergan Medical Optics, Irvine, CA, USA) or a foldable silicone IOL (SI-26NB, Allergan Medical Optics, Irvine, CA, USA). Gozum and colleagues[45] measured the contrast sensitivity of eyes with a rigid PMMA IOL (IOL type not specified; produced by Alcon Labs, Fort Worth, TX, USA), eyes with a foldable acrylic IOL (Acrysof, MA60BA, Alcon Labs, Forth Worth, TX, USA) and age-matched phakic eyes. Hollick and colleagues[46] measured the contrast sensitivity of eyes with a rigid PMMA IOL (MC60BM; Alcon, Forth Worth, TX, USA), a foldable silicone IOL (Iolab LI41U, Bausch & Lomb, Claremont, CA, USA) and a foldable acrylic IOL (Acrysof, MA60BM, Alcon Labs, Forth Worth, TX, USA). None of these studies found any difference in contrast sensitivity at optimal focus between spherical rigid PMMA IOLs and spherical foldable IOLs, which is in agreement with the results presented in this study.

To our knowledge, no study done previously has compared the optical quality of a foldable aspheric IOL and a rigid spherical PMMA IOL. In contrast, the optical quality of foldable spherical and aspheric IOLs has been compared extensively. Previous studies have shown that the aspheric IOL compensates for the corneal spherical aberration successfully.[20-34] However, no differences were found in the other higher-order aberrations between the foldable spherical and aspheric IOLs.[20,21,27] Our study confirms this finding: the aspheric IOL reduced the spherical aberration without changing the overall higher-order aberrations substantially.

In the present study, no difference in optimal contrast sensitivity measured under photopic conditions between the spherical, both rigid and foldable, and aspheric IOLs could be found. The majority of the studies done previously, however, found differences in optimal contrast sensitivity in favor of the aspheric IOL, especially under mesopic conditions.[20,21,23,24,30-33] Although contrast sensitivity was measured under photopic conditions in the present study, the use of a large artificial pupil combined with mydriasis should allow the uncovering of differences in optical performance, since this approach guarantees a high and constant retinal illumination, eliminating the influence of retinal illumination on contrast sensitivity.[14] Differences in spherical aberration were found, but the higher-order aberrations were similar in the three types of IOLs, which could explain the absence of any difference in contrast sensitivity at optimal focus and also the insignificant differences in depth of focus.

In a recent study, Nanavaty et al.[47] measured the depth of focus in eyes with the aspheric Acrysof SN60WF IOL (Alcon Labs, North Worth, TX, USA) and the spherical Acrysof SN60AT IOL (Alcon Labs, North Worth, TX, USA) and found a smaller depth of focus in eyes with the aspheric IOL (1.45 ± 0.74 D) compared to eyes with the spherical IOL (1.85 ± 0.75 D). In the present study, no difference in depth of focus was found between the foldable spherical group and the foldable aspheric group. This lack of difference could be explained by the method used to calculate the depth of focus. In the present study, depth of focus was defined as the dioptric range for which contrast sensitivity exceeds half of its maximum value (full width at half height [FWHH]),[40] whereas Nanavaty et al. defined depth of focus as the difference between the maximum refraction and minimum refraction of the refraction map of the iTrace Dynamic Laserefraction System (version 3.1.1; Tracy Technologies).[47]

Another contrast sensitivity related entity, the myopic shift, was, however, affected by the differences in spherical aberration. As noted previously, myopic shift is a shift of the optimal focus toward more myopic values at lower spatial frequencies, due to the presence of spherical aberration. Green and Campbell[48] already reported this nearly a half century ago. They had found a myopic shift of -0.9 D at 3 cpd when compared to the optimum focus measured at 45 cpd in healthy phakic subjects. Jansonius and Kooijman related myopic shift quantitatively to spherical aberration.[38] In the present study, the aspheric IOL successfully compensated for the spherical aberration of the human eye optics and, hence, resulted in a smaller myopic shift (-0.03 ± 0.41 D) compared to the spherical IOLs (MA30 IOLs: -0.39 ± 0.35 D; PMMA IOLs (-0.35 ± 0.21 D). This is in agreement with results reported by Denoyer et al.[21] and Bellucci et al.[28] Denoyer and colleagues measured the myopic shift in eyes with the aspheric Tecnis Z9000 IOL and the spherical CeeOn Edge 911 IOL, and found a myopic shift of -0.02 ± 0.36 D and of -0.51 ± 0.36 D respectively.[21] Bellucci and colleagues measured the myopic shift in four different spherical IOLs and in one aspheric IOL. They found a shift of -0.08 D in the aspheric IOL compared to shifts of -0.57 to -0.90 D in the spherical IOLs.[28]

Optimal contrast sensitivity at low spatial frequencies (3-5 cpd) is essential for viewing contours (edges); such low spatial frequencies are very sensitive to defocus.[49,50] When positive spherical aberration is present, optimal contrast sensitivity at low spatial frequencies is not reached with optimal refractive correction as determined using small optotypes, but is attained at a slightly more myopic correction. As a result, contrast contours are blurred at "optimal" focus; with a not-unrealistic myopic shift of -0.5 to -1 D, edge contrast sensitivity is reduced by 30 to 50% of its optimal value without a myopic shift.[50]

Whether spherical aberration is beneficial for the human eye optics or not is the subject of ongoing discussion. Higher-order aberrations, including spherical aberration, increase the depth of focus and, unless too many aberrations are present, they increase the depth of focus without significantly compromising visual acuity and contrast sensitivity at optimal focus. Hence, attempts to reduce aberrations are not meaningful without more. However, the unfavorable effects of a myopic shift, as already outlined in the previous paragraph, should not be neglected. In light of this, especially in eyes with more than average corneal spherical aberration, an aspheric IOL might be the most reasonable choice.

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