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Young eyes for elderly people

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Clinical comparison of the aspheric Tecnis ZA9003 and the spherical Sensar AR40e intraocular lenses

Spherical aberration, contrast sensitivity, depth of focus, myopic shift and straylight

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Abstract

Purpose

To compare the optical performance of the aspheric Tecnis ZA9003 and spherical Sensar AR40e intraocular lenses (IOLs).

Setting

Laboratory of Experimental Ophthalmology, University Medical Center Groningen, University of Groningen, Groningen, The Netherlands.

Methods

Thirty patients with bilateral senile cataract participated. A Tecnis IOL was implanted in one eye and a Sensar IOL in the other. Contrast sensitivity was measured using two computerized tests (vertical sine-modulated gratings and Holladay circular sine-modulated patterns) with cycloplegia and an artificial pupil of 5.0 mm under photopic conditions at optimal refractive correction and at several defocus levels. The depth of focus and the myopic shift (shift of optimal focus towards more myopic values at lower spatial frequencies) were determined. Higher-order aberrations were assessed using a Hartmann-Shack wavefront analyzer; straylight was measured with the C-Quant.

Results

No differences in contrast sensitivity at optimal focus, depth of focus and straylight were found between the two intraocular lenses. The mean spherical aberration was significantly lower in eyes with the Tecnis IOL (-0.036 µm) than with the Sensar IOL (0.064 µm; $P < .001$). The myopic shift was significantly smaller in eyes with the Tecnis IOL (0.05 D) than with the Sensar IOL (-0.47 D, $P < .001$).

Conclusions

Eyes with the Tecnis IOL showed a lower spherical aberration than eyes with the Sensar IOL and, related to that, a smaller myopic shift. No significant differences could be found in contrast sensitivity measured at optimal focus, in depth of focus and in straylight between the two IOLs.

Introduction

In cataract, changes in the crystalline lens lead to a loss of transparency which is associated with a loss of optical performance.[1] Replacing the cataractous lens with an artificial intraocular lens (IOL) results in an improvement in optical performance and a reduction in the amount of straylight.[2] Over the years, cataract extraction techniques have been optimized and patients' expectations for optimal postoperative optical performance have increased. Currently, research is being directed towards the design of intraocular lenses with optical properties more similar to those of the clear young human lens, while addressing both accommodation and aberrations.[3]

One of the most important aberrations of the human eye is the spherical aberration.[4] When spherical aberration is present, rays entering the periphery of the pupil are refracted to a different focal point than are rays entering near the center of the pupil, resulting in decreased contrast of the retinal image.[5,6] Generally, spherical aberration affects visual performance more when pupil diameters are larger.[7] With positive spherical aberration, peripheral rays are focused in front of the paraxial rays; with negative spherical aberration the peripheral rays are focused beyond the paraxial rays. The spherical aberration of the human eye is a combination of the positive spherical aberration of the cornea,[8-10] which is more or less constant throughout life,[10] and the negative spherical aberration of the lens.[11,12] In young eyes, the positive spherical aberration of the cornea is more or less compensated for by the negative spherical aberration of the lens and, as a result, the overall spherical aberration of the young eye is low.[9,10,13] With aging, the optical properties of the crystalline lens change,[11,14] resulting in an overall positive spherical aberration,[9,15,16] which results in loss of optical performance. A decline in the optical performance of the eye with age has been measured by Nio et al.,[17] Artal et al.[18] and Guirao et al.,[19] among others.

Initially, IOL designs were spherical, thus increasing the positive spherical aberration of the elderly cataract patient's optical system even more after a cataract extraction (a spherical surface has a positive spherical aberration).[20,21] Guirao et al. and Navarro et al. measured the optical modulation transfer function (oMTF) of patients with a spherical IOL and compared these results with measurements obtained from phakic subjects of various ages.[22,23] The oMTFs of pseudophakic patients were worse than the oMTFs of younger phakic subjects, but were comparable to the oMTFs of elderly subjects. These findings were confirmed using contrast sensitivity (CS) measurements performed on pseudophakic patients and phakic subjects of various ages.[24]

In 2002, Pharmacia/AMO introduced a new IOL design that was developed to compensate for the average positive spherical aberration of the cornea.[3] In 2004, the aspheric Tecnis Z9000 intraocular lens (Advanced Medical Optics, Santa Ana, CA, USA) received FDA approval. Several studies have investigated the optical performance of aspheric IOLs when compared to spherical IOLs.[3,25-43] However, contradictory results have been reported. A number of authors found a significant improvement in contrast sensitivity, especially under mesopic lighting conditions where the pupil diameter is larger than under photopic conditions, after implantation of an aspheric IOL,[25-39] but others did not.[40-43]

Differences in methodology might explain the controversy that still exists regarding the beneficial effects of the use of aspheric IOLs. Not only were different contrast sensitivity tests used in these studies, but also the pupil size (both natural and artificial) at which the contrast sensitivity test was performed differed considerably, which complicates any comparison among these studies. In an earlier study, we showed that computerized contrast sensitivity tests, together with cycloplegia and an artificial pupil, were necessary in order to uncover the influence of spherical aberration on contrast sensitivity.[44] With that in mind, this study was aimed at comparing the optical performance after cataract extraction of patients with an aspheric IOL (Tecnis ZA9003; Advanced Medical Optics [AMO], Santa Ana, CA, USA) in one eye and a spherical IOL (Sensar AR40e; AMO, Santa Ana, CA, USA) in the fellow eye using that methodology. In addition to the earlier studies cited above, we performed the contrast sensitivity measurements not only at optimal focus, but also at various levels of defocus. In all patients, spherical aberration and other higher-order aberrations were measured using a Hartmann-Shack Wavefront Sensor (Asclepion Meditec, Jena, Germany) so that the contrast sensitivity found could be better interpreted.

Methods

This double-masked randomized 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. The study was registered in the ISRCTN register, Trial Number ISCRTN17058178, and in the Dutch trial registers, Trial Number 813.

Subjects

Thirty-eight patients with bilateral age-related cataract, 20 female and 18 male patients, were recruited for this study. The mean age was 68.9 years, with a standard deviation of 12.0 years and a range from 28 to 87 years. 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 other words, any concurrent disease that might influence the optical or neural performance of the eye. Patients with a refractive error after cataract extraction in either eye of more than +/- 2 D spherical equivalent were excluded, as were patients with an astigmatism of more than 2.5 D. After implantation, best-corrected visual acuity (BCVA) was determined using an Early Treatment Diabetic Retinopathy Study (ETDRS) chart. The postoperative visual acuity of both eyes had to be at least 0.8 (20/25).

Intraocular lenses

Patients received the aspheric Tecnis ZA9003 (AMO, Santa Ana, CA, USA) in one eye and the spherical Sensar AR40e (AMO, Santa Ana, CA, USA) in the fellow eye. This was randomized with respect to left/right and first/last operated eye. The optical properties of the two IOLs are shown in Table 1.

Biometry was performed with an IOL-Master (Carl Zeiss Meditec AG, Jena, Germany). IOL power was chosen with the aim of obtaining an emmetropic postoperative refraction. All surgery was performed by the same experienced surgeon (SK), at the University Medical Center of Groningen, The Netherlands, using phacoemulsification through a 3.0 mm clear corneal incision at the 12:00 o'clock position and IOL implantation with an Emerald Injector (AMO, Santa Ana, CA, USA). Surgery of the second eye was scheduled at least one month after the first eye, in keeping with the guidelines of the Dutch Ophthalmological Society.

Assessments

Straylight measurements

Part of the light that enters the eye is scattered in the eye media rather than focused on the retina. This phenomenon is called straylight and decreases the contrast of the retinal image.[45,46] Straylight was measured with the C-Quant (Oculus, Wetzlar, Germany) with a natural pupil before the first and at least six weeks after the second eye surgery. The measurement was based on compensation comparison and has been described by Franssen and colleagues in detail.[47] In short, the stimulus consists of a flickering ring-shaped straylight source and a disc-shaped test field (divided into two halves) projected on a gray background. Compensation light (counterphase flicker with various modulation depths) is randomly presented in one of the two halves of the disk. Due to the straylight originating from the ring-shaped light source, both halves of the disk appear to flicker: one due to straylight only (test field without compensation light) and the other due to a combination of straylight and compensation light. After each change the subject is asked to indicate which half appears to flicker the most.

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

	Tecnis ZA9003 (AMO)	Sensar AR40e (AMO)
Optical		
Diameter (mm)	6.0	6.0
Shape	Equi-biconvex, modified prolate anterior surface	Biconvex
Material	UV-blocking hydrophobic acrylic	UV-blocking hydrophobic acrylic
Surface	Aspheric	Spherical
Estimated a-constant	119	118.6
Loop shape	Capsular C	Modified C
Loop Angulation (degrees)	6	10
Refractive index	1.46	1.46
Haptical		
Material	Polyvinylidene fluoride	Open-loop polymethyl methacrylate (PMMA), blue
IOL-Type	3 piece	3 piece
Length (mm)	12.0	13.0

Contrast sensitivity measurements

Contrast Sensitivity tests were performed at least six weeks after the second eye surgery under photopic conditions (85 cd/m^2). Measurements were performed with an artificial pupil of 5.0 mm in a trial frame, which relates to an average effective pupil size of 4.5 mm.[48] The pupil was dilated with two drops of tropicamide 0.5% and two drops of phenylephrine 2.5% (Chauvin Pharmaceuticals Ltd, Kingston-upon-Thames, Surrey, UK). Thirty minutes later, contrast sensitivity testing began. Contrast sensitivity was measured using two computerized tests (see below). Each test was performed at the recommended viewing distance, with optimal refraction for that viewing distance and with several defocus levels (-2D; -1D; -0.5D; +1D). Measurements were taken at two spatial frequencies, 3 and 6 cycles per degree (cpd). The order in which the spatial frequencies and defocus situations were tested was randomized. All contrast sensitivity tests were performed by a single investigator (KG) who was unaware as to which IOL was implanted in which eye, as was the patient.

The first computerized test (VSG; Cambridge Research Systems: VSG 2/3, version 4.02, Rochester, UK) generated vertical sine-modulated gratings on a cathode ray tube (Barco CCID7351B; Video & Communications N.V., Kortrijk, Belgium). This test was viewed at a distance of 2 m. We used the Von Békésy tracking method to assess the contrast threshold. In this method, the contrast is continuously changing. First, it increases until the pattern is observed by the subject. On pressing a button, the contrast begins to decrease until the subject stops being able to see the pattern. At that moment, the subject releases the button and the contrast starts to increase again. The contrast levels at which the gratings are reported as appearing and disappearing are recorded. Speed of change of contrast was set at 0.3 log/s.[49] Six upper and six lower reversals were measured. The first, highest and lowest values of both the upper and lower reversals were excluded, and the remaining upper and lower reversals were averaged, resulting in the contrast threshold.[49] The grating-pattern contrast is expressed in Michelson contrast:

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

where Lmax is the maximum luminance of the bright bars and Lmin the minimum luminance of the dark bars. Contrast sensitivity was defined as the inverse of the measured contrast threshold.

The other computerized test was the Holladay automated contrast sensitivity testing system (HACSS; M&S Technologies, Skokie, Il, USA). Circular sine-modulated patterns were used. The test begins with 50% contrast, starting at 6 cpd. The subject is asked to indicate whether the displayed stimulus is a circular pattern or a blank disk. Throughout the test, several blank disks are shown at the same mean luminance level so as to check reliability. 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. The contrast threshold corresponds to the lowest contrast level at which the subject can identify two out of three circular patterns correctly. Contrast sensitivity is defined as the reciprocal of this contrast threshold and is based on Michelson contrast (Eq [1]). This test was performed at the recommended viewing distance of 4 m.

Spherical aberration measurements

The spherical aberration of the whole eye is a combination of the spherical aberration that originates from the cornea[8-10] and the spherical aberration that originates from the crystalline lens.[11,12] In this study, the corneal contribution of the spherical aberration was calculated by using the mean power keratometric pictures from the Orbscan (Orbscan II, version 3.12, Bausch & Lomb, Inc., Rochester, NY, USA), following a methodology as published by Nio and colleagues.[50] Corneal topography was performed before the first eye surgery and six weeks after the second eye surgery.

Wavefront aberrations of the whole eye were measured after cataract surgery using a wavefront analyzer (WASCA version 1.26.3; Asclepion Meditec, Jena, Germany) and are presented in standardized Optical Society of America (OSA) values.[51] 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 aberration coefficients from the 3rd to the 6th order was used as a measure of higher-order aberrations. The sign of the bilaterally antisymmetrical coefficients c_3^x where reversed for right eyes.[52-54] Wavefront aberrations were measured after cycloplegia and mydriasis, and calculated for a 5.0 mm apparent pupil (which is about 12% larger than the effective pupil size[48] as used in the WASCA software). The results of the wavefront aberration measurements were not available during the contrast sensitivity testing.

Statistical analysis

The main outcome variable of the contrast sensitivity test was the logarithmic value of contrast sensitivity (logCS). ANOVA General Linear Model (GLM) for repeated measurements and post-hoc analysis (a t-test for paired samples) with Bonferroni correction were performed in order to identify the effects on the logCS values of the various levels of defocus and between the IOL types. The t-test for the paired samples with Bonferroni correction was used to explore the differences in wavefront aberrations. The t-test for paired samples was used to explore differences in visual acuity, depth of focus, myopic shift and straylight between the IOLs. To obtain reliable straylight values, the straylight parameter (log(s)) had to be less than 2.5 in both eyes with a standard deviation of less than 0.12.[55-57]

Depth of focus and myopic shift

Depth of focus and myopic shift (shift of optimal focus towards more myopic values at lower spatial frequencies due to spherical aberration)[6,50] were determined by fitting a parabola through the logCS as a function of defocus curve (through-focus curve) at 6 cpd. For statistical accuracy, the R^2 of the fitted parabola had to be at least 0.85 in both eyes and the highest contrast sensitivity value was not allowed to correspond to one of the two extreme defocus values (-2 D and the +1 D) in either eye. Subsequently, depth of focus was defined as the dioptric range for which contrast sensitivity exceeds half of its maximum value.[58] 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.

Results

Patients

Of the 38 recruited patients, 30 were included in the study. Two patients were excluded because they changed their minds concerning their participation, three patients because the BCVA after the cataract extraction was lower than the required minimum value of 0.8 (see Methods) in at least one eye, one because of a high cylindrical correction after surgery, one because of a capsular rupture during the surgery and one because the patient could not complete the contrast sensitivity tests successfully. The mean age of the remaining 30 patients was 69.2 years, with a standard deviation of 10.4 years and a range from 45 to 87 years. Mean IOL power was 20.4 D (standard deviation 4.0 D; range 12.5 to 27.0 D) for the Tecnis IOL and 20.0 D (standard deviation 4.0 D; range 11.0 to 27.0 D) for the Sensar IOL. BCVA measured in eyes with the Tecnis IOL and the Sensar IOL was, respectively, 1.07 (decimal notation; standard deviation 0.17) and 1.11 (standard deviation 0.17). The difference in BCVA between both IOLs was not significant ($P = .07$).

Wavefront aberrations and straylight

Figure 1 shows the aberration coefficients (mean +/- standard error of the mean) up to the sixth order Zernike polynomial of eyes with the Sensar and the Tecnis intraocular lenses. No statistically significant differences were found in any of the wavefront aberration coefficients except for that of the Zernike polynomial Z_4^0. The overall value (root of the sum of the squares) of all higher-order aberrations together was 0.262 µm (standard deviation 0.096 µm) in eyes with the Sensar IOL and 0.234 µm (standard deviation 0.071 µm) in eyes with the Tecnis IOL. This difference was not significant ($P = .171$).

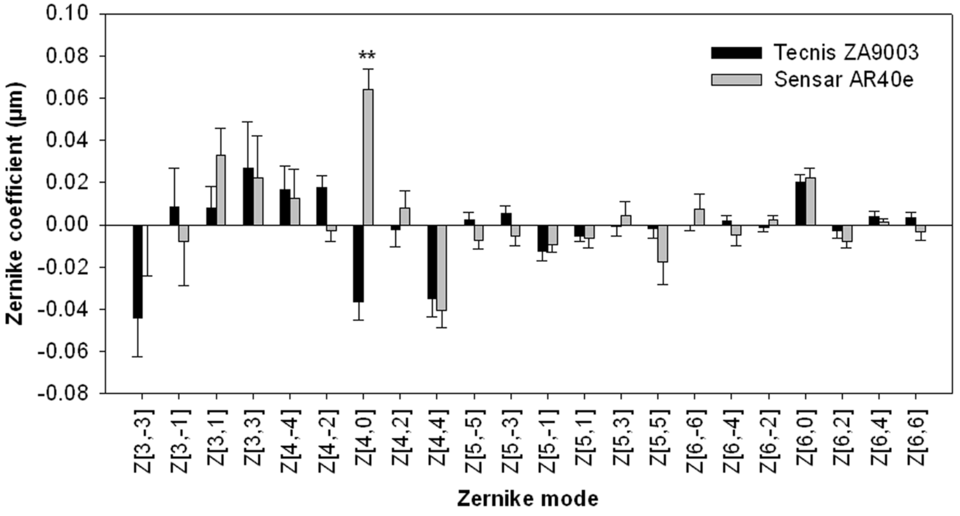

Figure 1. *Representation of the aberration coefficients (mean +/- standard error of the mean; artificial pupil size = 5.0 mm) of Zernike polynomials up to the sixth order as measured in eyes with the Tecnis ZA9003 IOL (black bars) and the Sensar AR40e IOL (gray bars). ** P < .001.*

Figure 2 shows the spherical aberration values measured in eyes with the Sensar IOL and in those with the Tecnis IOL, measured for each patient separately. The mean spherical aberration in eyes with the Sensar IOL was 0.064 µm (standard deviation 0.052 µm; range -0.06 to 0.17 µm) and in eyes with the Tecnis IOL it was -0.036 µm (standard deviation 0.047 µm; range -0.15 to 0.04 µm; *P* < .001). The mean absolute c_4^0 coefficient was 0.070 µm (standard deviation 0.043 µm) for eyes with the Sensar IOL and 0.049 µm (standard deviation 0.034 µm; *P* = .076) for eyes with the Tecnis IOL. The mean of the primary and secondary spherical aberration coefficients together, $\sqrt{((c_4^0)^2 + (c_6^0)^2)}$, appeared to be significantly larger in eyes with the Sensar IOL (0.079 µm; standard deviation 0.039 µm) compared to eyes with the Tecnis IOL (0.056 µm; standard deviation 0.034 µm; *P* = .043).

The mean preoperative corneal spherical aberration (0.09 µm, standard deviation 0.09 µm) differed statistically significantly from the mean postoperative corneal spherical aberration (0.12 µm, standard deviation 0.08 µm, n=40; *P* = .009) when measured six weeks after the second eye surgery. There was no significant difference in the mean corneal spherical aberration between eyes with the Sensar IOL (0.13 µm, standard deviation 0.08 µm, n=20) and the Tecnis IOL (0.10 µm, standard deviation 0.08 µm D, n=20; *P* = .112).

Spherical aberration data for the cornea of 10 patients were not analyzed because reliable data were lacking for at least one eye due to either tear film irregularities or fixation instability, that disturbed the measurements.

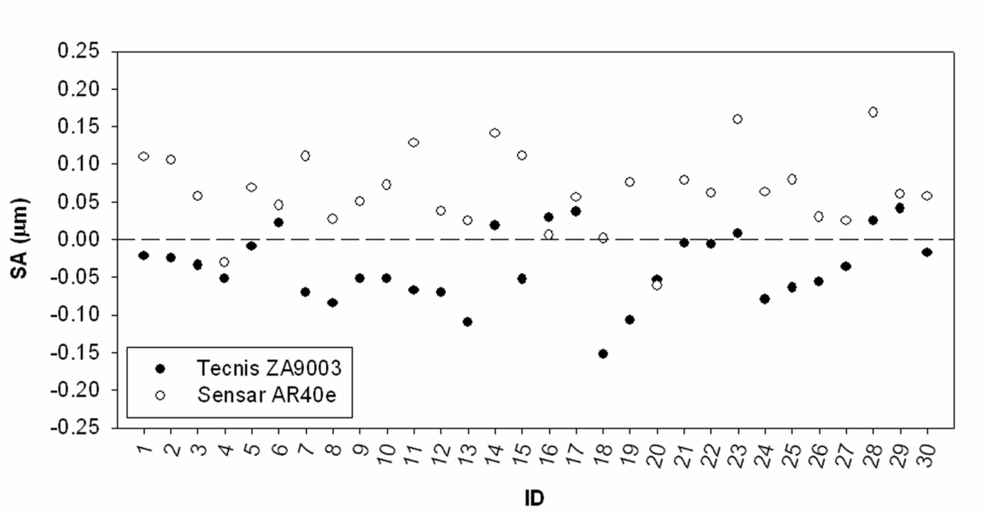

Figure 2. *Representation of the spherical aberration measured in eyes with the Tecnis ZA9003 IOL and the Sensar AR40e IOL for each patient separately. Measurements were performed with a 5.0 mm artificial pupil (SA = spherical aberration, ID = patient number).*

Figure 3 shows the relationship between the overall (that is, of cornea and lens together) spherical aberration after the cataract extraction and the corneal spherical aberration before the cataract extraction. There was no preoperative difference in corneal spherical aberration in eyes receiving either the Sensar IOL or the Tecnis IOL. After implantation, the eyes with the Sensar IOL showed a significantly higher total spherical aberration than the eyes with the Tecnis IOL, although the difference, in terms of absolute values, was small. The distributions of overall spherical aberration as found in eyes with the Tecnis and Sensar intraocular lenses are comparable with those distributions found in young (black bar) and old (gray bar) phakic eyes, respectively.[44]

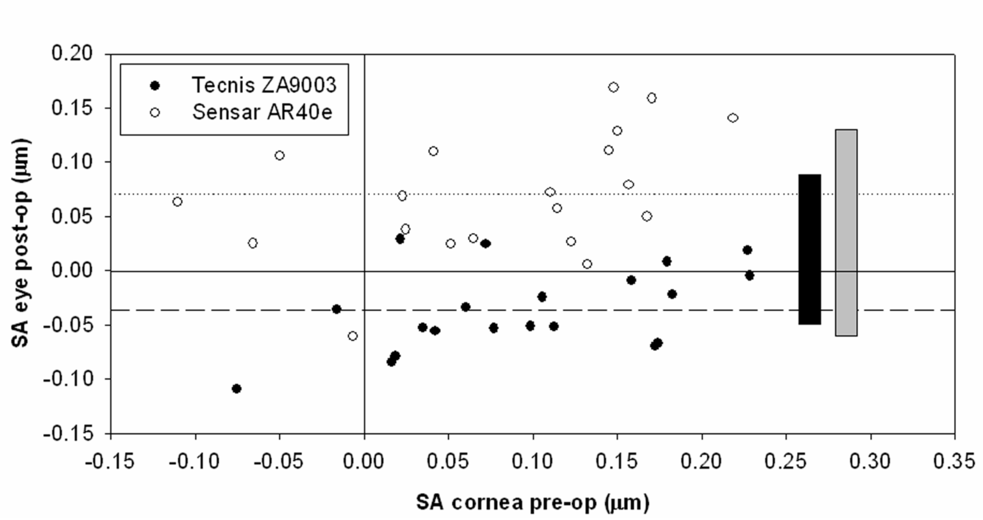

Figure 3. *Overall spherical aberration measured with a 5.0 mm artificial pupil after cataract extraction as a function of the corneal spherical aberration before cataract extraction. Open circles represent eyes with the Sensar AR40e IOL, solid circles eyes with the Tecnis ZA9003 IOL. The average value of the spherical aberration measured in eyes with the Tecnis ZA9003 IOL is represented with the dashed line, and for eyes with the Sensar AR40e with the dotted line. Bars represent the distribution of overall spherical aberration as found in young (black bar) and elderly (gray bar) healthy phakic subjects (SA = spherical aberration).*[44]

Figure 4 shows the straylight measured pre- and postoperatively. Straylight decreased significantly after cataract extraction (preoperative mean value 1.88 log(s), standard deviation 0.38, n=48; postoperative mean value 1.36 log(s), standard deviation 0.26, n=48; *P* < .001). There was no significant difference in straylight between eyes with the Sensar IOL (mean value 1.38 log(s), standard deviation 0.25, n=29) and the Tecnis IOL (mean value 1.38 log(s), standard deviation 0.26, n=29; *P* = .92).

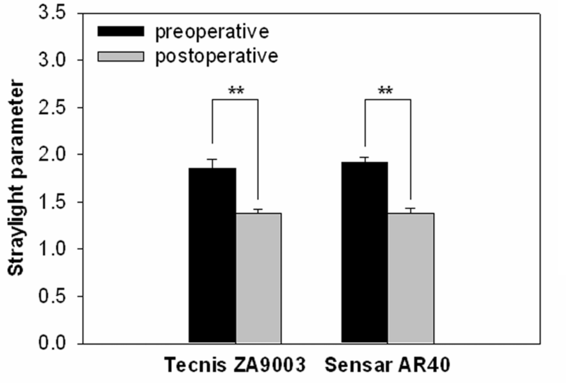

Figure 4. *Straylight measured with a natural pupil preoperatively (black bars) and postoperatively (gray bars) in eyes with the Tecnis ZA9003 and the Sensar AR40e lens. Error bars represent the standard error of the mean. ** P < .001.*

Contrast sensitivity, depth of focus and myopic shift

With optimal focus and a 5.0 mm pupil, contrast sensitivity measurements with the VSG and HACSS showed no differences between the Tecnis and Sensar intraocular lenses, either at 3 cpd or at 6 cpd (Table 2). Figure 5 shows the through-focus curves measured at 3 and 6 cpd for both the VSG and the HACSS. Eyes with the Tecnis IOL showed a significantly lower contrast sensitivity when -2D defocus was applied for the VSG at 6 cpd (*P* = .001), and the HACSS at 3 cpd (*P* = .001) and 6 cpd (*P* = .003). When measured with the VSG at 3 cpd, the difference (*P* = .028) was not statistically significant due to Bonferroni correction.

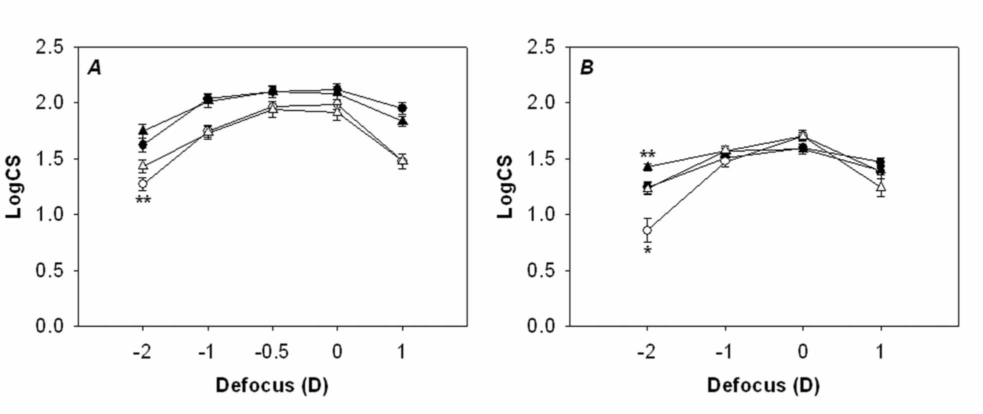

Figure 5. *Through-focus curves (mean +/- standard error of the mean; artificial pupil size = 5.0 mm) for the VSG (**A**) and the HACSS (**B**). Circles represent measurements performed on eyes with the Tecnis ZA9003 IOL; triangles on eyes with the Sensar AR40e IOL. Solid symbols represent measurements performed at 3 cpd; open symbols at 6 cpd (LogCS = log contrast sensitivity).*
** P ≤ .01; ** P ≤ .001.*

Table 2. *Contrast senitivity measured for both IOL groups (mean logCS ± SD (range)) in a 5.0 mm artificial pupil.*

	Mean LogCS ± SD (Range)		
	Tecnis ZA9003	Sensar AR40e	*P* value
HACSS at 3 cpd	1.60 ± 0.16 (1.20-1.85)	1.59 ± 0.23 (1.20-2.40)	.82
HACSS at 6 cpd	1.70 ± 0.27 (1.30-2.40)	1.70 ± 0.20 (1.30-2.10)	.92
VSG at 3 cpd	2.12 ± 0.28 (1.32-2.62)	2.12 ± 0.27 (1.63-2.82)	.98
VSG at 6 cpd	1.99 ± 0.25 (1.56-2.49)	1.96 ± 0.30 (1.42-2.70)	.46

cpd = cycles per degree; HACSS Holladay circular sine-modulated patterns; LogCS = log contrast sensitivity; VSG = vertical sine-modulated gratings

Depth of focus and myopic shift were determined in both eyes for a subset (see Methods) of 19 patients, using measurements performed with the HACSS (too few patients met the criteria for depth of focus evaluation in both eyes with VSG). No significant difference in depth of focus was found between eyes with the Tecnis IOL (2.41 ± 0.63 D) and the Sensar IOL (2.67 ± 0.72 D; $P = .15$). Figure 6, *A* shows the myopic shift for eyes with the Tecnis IOL and the Sensar IOL. The myopic shift of the eyes with the Tecnis IOL (0.05 ± 0.40 D) was significantly smaller than that of the eyes with the Sensar IOL (-0.47 ± 0.32 D; $P < .001$). Figure 6, *B* presents the myopic shift as a function of spherical aberration. A significant relationship between myopic shift and spherical aberration was found (slope = -3.9 D/µm, $R^2 = 0.38$, $P < .001$).

Discussion

This study compared the monochromatic aberrations and the optical performance of the aspheric Tecnis ZA9003 IOL with that of its spherical counterpart, the Sensar AR40e IOL. Both IOLs were made by the same manufacturer from hydrophobic acrylate material. Implantation of the Tecnis IOL resulted in a significantly lower spherical aberration and, related to that, in less myopic shift. No differences in contrast sensitivity measured at optimal focus, and none in depth of focus and straylight were found.

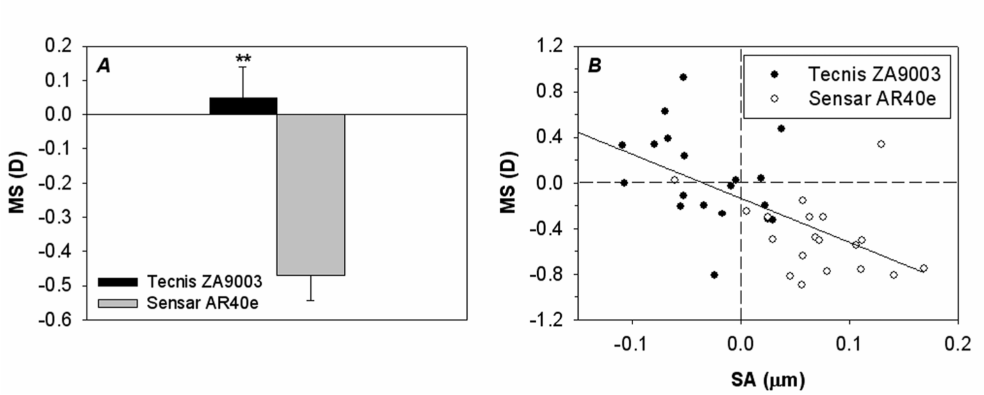

Figure 6. *Myopic shift measured with an artificial pupil of 5.0 mm for eyes with the Tecnis ZA9003 IOL (black bar) and the Sensar AR40e IOL (gray bar) (**A**) and the myopic shift as a function of spherical aberration (**B**). Open circles represent eyes with the Sensar IOL, solid circles eyes with the Tecnis IOL. Error bars represent the standard error of the mean (MS = myopic shift; SA = spherical aberration). ** P < .001.*

The main goal of the aspheric IOL is to compensate for the spherical aberration of the human cornea with the aim of restoring the optical performance of the eye.[3] All studies done previously were successful in showing the ability of the aspheric IOL to significantly lower the overall spherical aberration of the eye,[25,27,28,30,33-43,59-61] and some studies demonstrated a related improvement in optical performance. Improvements in visual acuity and contrast sensitivity in favor of the aspheric IOL have been reported by Mester et al., Packer et al., Muñoz et al., Bellucci et al. and Kim et al., among others. The Tecnis Z9000 IOL (AMO, Santa Ana, CA, USA) was the first aspheric IOL, and therefore more studies have been done with this silicone IOL than with the acrylic Tecnis ZA9003 IOL as used in this study.[25-27,29,31-33,36,39,41-43,59-61] To our knowledge, only one publication is available that reports on the clinical performance of the aspheric ZA9003 IOL in comparison with a spherical IOL. Kim and colleagues compared the aspheric Tecnis ZA9003 IOL with the spherical Acrysof SA60AT IOL (Alcon Labs, North Worth, TX, USA) and found an improvement in contrast sensitivity under both mesopic and photopic conditions that favored the Tecnis ZA9003 IOL.[28] The mean spherical aberration was significantly higher in eyes with the Acrysof SA60AT IOL, whereas the total higher-order aberrations did not differ significantly. Some authors found an increase in depth of focus when residual spherical aberration was present. For example, Johansson and colleagues measured, using a 5.0 mm pupil, a spherical aberration of 0.03 ± 0.06 μm and a depth of focus of 0.78 ± 0.47 D in eyes with the Tecnis Z9000 IOL and of 0.17 ± 0.06 μm and 0.97 ± 0.41 D in eyes with the Akreos Adapt AO IOL (Bausch & Lomb, Inc., Rochester, NY, USA), respectively (the lower depth of focus value as compared to our depth of focus values is the result of a different definition of depth of focus).[41] Contrary to the authors mentioned above, Muñoz et al.[43], Kasper et al.[42] and Kurz et al.[40] did not find statistically significant differences in visual acuity and contrast sensitivity between spherical and aspheric IOLs.[42,43]

Spherical aberration can cause a shift in the through-focus curve at low spatial frequencies, rendering the eye more myopic: myopic shift.[6] Denoyer and colleagues measured the myopic shift in eyes with the aspheric Tecnis Z9000 IOL and the spherical CeeOn Edge 911 IOL, and found myopic shifts of -0.02 D ± 0.36 D and -0.51 D ± 0.36 D, respectively.[27] Bellucci and colleagues measured the myopic shift in eyes with four different spherical IOLs and in one aspheric IOL. Eyes with the aspheric IOL had a significantly smaller myopic shift (-0.08 D) compared to eyes with the spherical IOLs (-0.57 D to -0.90 D).[61] These findings are in agreement with the present study.

Myopic shift might be harmful. For example, if the refraction has been optimized for viewing small details (as is usually the case) for a given distance, then the observed contrast of contours (edges) will be lower if a myopic shift is present. This is a consequence of the fact that the spatial frequencies needed for edge detection are around 3-5 cpd and very sensitive to defocus.[62,63]

The most important explanation for the lack of difference in contrast sensitivity and depth of focus found in this study is that, although there were small differences in spherical aberration, the overall higher-order aberrations were similar in both the spherical and aspheric IOLs. We found less spherical aberration in eyes with the Sensar IOL than is commonly found in eyes with spherical IOLs. Mester and colleagues[25], however, found statistically significant differences in contrast sensitivity between the spherical and aspheric IOLs, with similar small differences in spherical aberration; in their study, mean spherical aberration in eyes with the Tecnis Z9000 IOL was 0.001 ± 0.026 μm and 0.074 ± 0.026 μm in eyes with the SI-40 IOL (Allergan Inc., Irvine, CA, USA). This difference as compared to our findings might be related to a smaller variability in their sample (their standard deviations of 0.026 μm should be compared to our standard deviations of 0.047 and 0.052 μm).

Because we found similar small mean spherical aberrations in both groups, we redivided the eyes of our patients into two groups: eyes that had spherical aberration values nearest to zero (whichever IOL had been implanted) were attributed to Group I; Group II contained the fellow eyes. This yielded a mean spherical aberration in Group I of -0.0004 µm and of 0.0282 µm in Group II. No difference in contrast sensitivity could be measured after this redistribution either.

The lack of potential benefits from the aspheric IOL as found in our study could also be partly due to the specific design or material. Most of the studies cited above compared IOLs either made of different material (silicone versus acrylic) or from different manufacturers or both, whereas we compared two IOLs of the same material and by the same manufacturer. That is probably also the reason why no difference in straylight was found between the Sensar IOL and the Tecnis IOL. The design, material and refractive index could all play a role in the amount of induced aberrations.[64] Tognetto and colleagues[65] studied the optical properties of 24 different types of IOLs on an optical test bench. They reported that the acrylic IOLs were – without exception - superior to the silicone IOLs in terms of their modulation transfer function.

Not only the optical properties of the IOL are of importance, but also the centration of the IOL in the eye. Holladay and colleagues showed an improvement in optical performance of the aspheric IOL compared to the spherical IOL if centered within 0.4 mm and tilted less than 7 degrees.[3] Decentration of the IOL resulted in an increase in coma-like aberrations. In our study, however, no significant amounts of coma-like aberrations (depicted by the root of the sum of the squares of the aberration coefficients c_3^{-1},c_3^{1}, c_5^{-1} and c_5^{1} were present (Sensar IOL: 0.123 µm ± 0.067; Tecnis IOL: 0.109 µm ± 0.049; P = .321). This corroborates the results of Bellucci et al. and Denoyer et al., among others. Therefore, decentration of the IOL, as an explanation of the absence of a difference in optical performance between the two IOL types, is unlikely.

In conclusion, the Tecnis IOL tends to overcompensate the corneal spherical aberration in eyes with little corneal spherical aberration, resulting in a negative overall spherical aberration. In eyes with a higher than average corneal spherical aberration, the total spherical aberration will be close to zero if a Tecnis is implanted. Whether or not some spherical aberration is favorable (increase in depth of focus) or unfavorable (myopic shift), and related to that what IOL should be preferred in clinical practice given a certain amount of corneal spherical aberration, should be the subject of future research.

References

1. Foster A, Johnson GJ. Magnitude and causes of blindness in the developing world. Int Ophthalmol 1990; 14:135-140
2. Van Den Berg TJ, Van Rijn LJ, Michael R, et al. Straylight effects with aging and lens extraction. Am J Ophthalmol 2007; 144:358-363
3. Holladay JT, Piers PA, Koranyi G, et al. A new intraocular lens design to reduce spherical aberration of pseudophakic eyes. J Refract Surg 2002; 18:683-691
4. Porter J, Guirao A, Cox IG, Williams DR. Monochromatic aberrations of the human eye in a large population. J Opt Soc Am A Opt Image Sci Vis 2001; 18:1793-1803
5. Green DG, Campbell FW. Effect of focus on visual response to a sinusoidally modulated spatial stimulus. Journal of the Optical Society of America 1965; 55:1154-1157
6. Jansonius NM, Kooijman AC. The effect of spherical and other aberrations upon the modulation transfer of the defocussed human eye. Ophthalmic Physiol Opt 1998; 18:504-513
7. Oshika T, Tokunaga T, Samejima T, et al. Influence of pupil diameter on the relation between ocular higher-order aberration and contrast sensitivity after laser in situ keratomileusis. Invest Ophthalmol Vis Sci 2006; 47:1334-1338
8. Artal P, Berrio E, Guirao A, Piers P. Contribution of the cornea and internal surfaces to the change of ocular aberrations with age. J Opt Soc Am A Opt Image Sci Vis 2002; 19:137-143
9. Guirao A, Redondo M, Artal P. Optical aberrations of the human cornea as a function of age. J Opt Soc Am A Opt Image Sci Vis 2000; 17:1697-1702
10. Oshika T, Klyce SD, Applegate RA, Howland HC. Changes in corneal wavefront aberrations with aging. Invest Ophthalmol Vis Sci 1999; 40:1351-1355
11. Glasser A, Campbell MC. Biometric, optical and physical changes in the isolated human crystalline lens with age in relation to presbyopia. Vision Res 1999; 39:1991-2015
12. Smith G, Cox MJ, Calver R, Garner LF. The spherical aberration of the crystalline lens of the human eye. Vision Res 2001; 41:235-243
13. El Hage SG, Berny F. Contribution of the crystalline lens to the spherical aberration of the eye. J Opt Soc Am 1973; 63:205-211
14. Dubbelman M, Van der Heijde GL. The shape of the aging human lens: curvature, equivalent refractive index and the lens paradox. Vision Res 2001; 41:1867-1877
15. Amano S, Amano Y, Yamagami S, et al. Age-related changes in corneal and ocular higher-order wavefront aberrations. Am J Ophthalmol 2004; 137:988-992
16. McLellan JS, Marcos S, Burns SA. Age-related changes in monochromatic wave aberrations of the human eye. Invest Ophthalmol Vis Sci 2001; 42:1390-1395
17. Nio YK, Jansonius NM, Fidler V, et al. Age-related changes of defocus-specific contrast sensitivity in healthy subjects. Ophthalmic Physiol Opt 2000; 20:323-334

18. Artal P, Ferro M, Miranda I, Navarro R. Effects of aging in retinal image quality. J Opt Soc Am A 1993; 10:1656-1662
19. Guirao A, Gonzalez C, Redondo M, et al. Average optical performance of the human eye as a function of age in a normal population. Invest Ophthalmol Vis Sci 1999; 40:203-213
20. Taketani F, Yukawa E, Yoshii T, et al. Influence of intraocular lens optical design on high-order aberrations. J Cataract Refract Surg 2005; 31:969-972
21. Barbero S, Marcos S, Jimenez-Alfaro I. Optical aberrations of intraocular lenses measured in vivo and in vitro. J Opt Soc Am A Opt Image Sci Vis 2003; 20:1841-1851
22. Guirao A, Redondo M, Geraghty E, et al. Corneal optical aberrations and retinal image quality in patients in whom monofocal intraocular lenses were implanted. Arch Ophthalmol 2002; 120:1143-1151
23. Navarro R, Ferro M, Artal P, Miranda I. Modulation transfer-functions of eyes implanted with intraocular lenses. Applied Optics 1993; 32:6359-6367
24. Nio YK, Jansonius NM, Geraghty E, et al. Effect of intraocular lens implantation on visual acuity, contrast sensitivity, and depth of focus. J Cataract Refract Surg 2003; 29:2073-2081
25. Mester U, Dillinger P, Anterist N. Impact of a modified optic design on visual function: clinical comparative study. J Cataract Refract Surg 2003; 29:652-660
26. Bellucci R, Scialdone A, Buratto L, et al. Visual acuity and contrast sensitivity comparison between Tecnis and AcrySof SA60AT intraocular lenses: A multicenter randomized study. J Cataract Refract Surg 2005; 31:712-717
27. Denoyer A, Le Lez ML, Majzoub S, Pisella PJ. Quality of vision after cataract surgery after Tecnis Z9000 intraocular lens implantation: effect of contrast sensitivity and wavefront aberration improvements on the quality of daily vision. J Cataract Refract Surg 2007; 33:210-216
28. Kim SW, Ahn H, Kim EK, Kim TI. Comparison of higher order aberrations in eyes with aspherical or spherical intraocular lenses. Eye 2008; 22:1493-1498
29. Kershner RM. Retinal image contrast and functional visual performance with aspheric, silicone, and acrylic intraocular lenses. Prospective evaluation. J Cataract Refract Surg 2003; 29:1684-1694
30. Tzelikis PF, Akaishi L, Trindade FC, Boteon JE. Spherical aberration and contrast sensitivity in eyes implanted with aspheric and spherical intraocular lenses: a comparative study. Am J Ophthalmol 2008; 145:827-833
31. Packer M, Fine IH, Hoffman RS, Piers PA. Prospective randomized trial of an anterior surface modified prolate intraocular lens. J Refract Surg 2002; 18:692-696
32. Packer M, Fine IH, Hoffman RS, Piers PA. Improved functional vision with a modified prolate intraocular lens. J Cataract Refract Surg 2004; 30:986-992
33. Bellucci R, Morselli S. Optimizing higher-order aberrations with intraocular lens technology. Curr Opin Ophthalmol 2007; 18:67-73
34. Sandoval HP, Fernandez de Castro LE, Vroman DT, Solomon KD. Comparison of visual outcomes, photopic contrast sensitivity, wavefront analysis, and patient satisfaction following cataract extraction and IOL implantation: aspheric vs spherical acrylic lenses. Eye 2008; 22:1469-1475

35. Tzelikis PF, Akaishi L, Trindade FC, Boteon JE. Ocular aberrations and contrast sensitivity after cataract surgery with AcrySof IQ intraocular lens implantation Clinical comparative study. J Cataract Refract Surg 2007; 33:1918-1924
36. Padmanabhan P, Rao SK, Jayasree R, et al. Monochromatic aberrations in eyes with different intraocular lens optic designs. J Refract Surg 2006; 22:172-177
37. Marcos S, Barbero S, Jimenez-Alfaro I. Optical quality and depth-of-field of eyes implanted with spherical and aspheric intraocular lenses. J Refract Surg 2005; 21:223-235
38. Mester U, Kaymak H. Comparison of the AcrySof IQ aspheric blue light filter and the AcrySof SA60AT intraocular lenses. J Refract Surg 2008; 24:817-825
39. Caporossi A, Martone G, Casprini F, Rapisarda L. Prospective randomized study of clinical performance of 3 aspheric and 2 spherical intraocular lenses in 250 eyes. J Refract Surg 2007; 23:639-648
40. Kurz S, Krummenauer F, Thieme H, Dick HB. Contrast sensitivity after implantation of a spherical versus an aspherical intraocular lens in biaxial microincision cataract surgery. J Cataract Refract Surg 2007; 33:393-400
41. Johansson B, Sundelin S, Wikberg-Matsson A, et al. Visual and optical performance of the Akreos Adapt Advanced Optics and Tecnis Z9000 intraocular lenses: Swedish multicenter study. J Cataract Refract Surg 2007; 33:1565-1572
42. Kasper T, Buhren J, Kohnen T. Visual performance of aspherical and spherical intraocular lenses: intraindividual comparison of visual acuity, contrast sensitivity, and higher-order aberrations. J Cataract Refract Surg 2006; 32:2022-2029
43. Muñoz G, Albarran-Diego C, Montes-Mico R, et al. Spherical aberration and contrast sensitivity after cataract surgery with the Tecnis Z9000 intraocular lens. J Cataract Refract Surg 2006; 32:1320-1327
44. Van Gaalen KW, Jansonius NM, Koopmans SA, et al. Relationship between contrast sensitivity and spherical aberration: comparison of 7 contrast sensitivity tests with natural and artificial pupils in healthy eyes. J Cataract Refract Surg 2009; 35:47-56
45. Van den Berg TJTP. Importance of pathological intraocular light scatter for visual disability. Doc. Ophthalmol. 1986;61:327-33
46. Elliot DB, Bullimore MA. Assessing the reliability, discriminative ability, and validity of disability glare tests. IOVS 1993;34:108-119
47. Franssen L, Coppens JE, Van Den Berg TJ. Compensation comparison method for assessment of retinal straylight. Invest Ophthalmol Vis Sci 2006; 47:768-776
48. Kooijman AC. Light distribution on the retina of a wide-angle theoretical eye. J Opt Soc Am 1983; 73:1544-1550
49. Nio YK, Jansonius NM, Lamers P, et al. Influence of the rate of contrast change on the quality of contrast sensitivity assessment: a comparison of three psychophysical methods. Ophthalmic Physiol Opt 2005;25:18-26
50. Nio YK, Jansonius NM, Fidler V, et al. Spherical and irregular aberrations are important for the optimal performance of the human eye. Ophthalmic Physiol Opt 2002; 22:103-112

51. Thibos LN, Applegate RA, Schwiegerling JT, Webb R. Standards for reporting the optical aberrations of eyes. J Refract Surg 2002; 18:S652-S660
52. Howland HC, Howland B. A subjective method for the measurement of monochromatic aberrations of the eye. J Opt Soc Am 1977;67:1508-1518
53. Kelly JE, Mihashi T, Howland HC. Compensation of corneal horizontal/vertical astigmatism, lateral coma, and spherical aberration by internal optics of the eye. J Vis 2004;4:262-271
54. Smolek MK, Klyce SD, Sarver EJ. Inattention to nonsuperimposable midline symmetry causes wavefront analysis error. Arch Ophthalmol 2002;120:439-447
55. Van den Berg TJTP, Van Rijn LJ, Micheal R et al. Straylight effects with aging and lens extraction. Am. J. Ophthalmol 2007;144:358-363.
56. Coppens JE, Franssen L, Van Den Berg TJ. Reliability of the compensation comparison method for measuring retinal stray light studied using Monte-Carlo simulations. J Biomed Opt. 2006;11:054010.
57. Coppens JE, Franssen L, Van Rijn LJ, Van Den Berg TJ. Reliability of the compensation comparison stray-light measurement method. J Biomed Opt. 2006;11:34027.
58. Legge GE, Mullen KT, Woo GC, Campbell FW. Tolerance to visual defocus. J Opt Soc Am A 1987; 4:851-863
59. Kasper T, Buhren J, Kohnen T. Intraindividual comparison of higher-order aberrations after implantation of aspherical and spherical intraocular lenses as a function of pupil diameter. J Cataract Refract Surg 2006; 32:78-84
60. Bellucci R, Morselli S, Pucci V. Spherical aberration and coma with an aspherical and a spherical intraocular lens in normal age-matched eyes. J Cataract Refract Surg 2007; 33:203-209
61. Bellucci R, Morselli S, Piers P. Comparison of wavefront aberrations and optical quality of eyes implanted with five different intraocular lenses. J Refract Surg 2004; 20:297-306
62. Jansonius NM, Kooijman AC. The effect of defocus on edge contrast sensitivity. Ophthalmic Physiol Opt 1997; 17:128-132
63. King-Smith PE, Kulikowski JJ. Line, edge and grating detectors in human vision. J Physiol 1972; 230:23P-25P
64. Dick HB, Krummenauer F, Schwenn O, et al. Objective and subjective evaluation of photic phenomena after monofocal and multifocal intraocular lens implantation. Ophthalmology 1999; 106:1878-1886
65. Tognetto D, Sanguinetti G, Sirotti P, et al. Analysis of the optical quality of intraocular lenses. Invest Ophthalmol Vis Sci 2004; 45:2682-2690