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Young eyes for elderly people

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Document Version

Publisher's PDF, also known as Version of record

Publication date:
2009

[Link to publication in University of Groningen/UMCG research database](#)

Citation for published version (APA):

Galen, K. W. V. (2009). *Young eyes for elderly people: a clinical comparison of spherical and aspheric intraocular lenses*. s.n.

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Depth of focus of the aspheric Tecnis ZA9003 and the spherical Sensar AR40e intraocular lenses

A comparison of two different definitions

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Abstract

Purpose

To compare depth of focus of eyes with the aspheric Tecnis ZA9003 intraocular lens (IOL) with that of eyes with the spherical Sensar AR40e IOL, using two different definitions of depth of focus, and to relate the depth of focus to the amount of spherical aberration.

Setting

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

Methods

Thirty patients with a Sensar AR40e IOL in one eye and a Tecnis ZA9003 IOL in the fellow eye participated. Contrast sensitivity was measured using the Holladay circular sine-modulated patterns test with an artificial pupil of 5.0 mm. Contrast sensitivity was measured at optimal refractive correction and at three defocus levels; -2 D, -1 D and +1 D. Depth of focus of the eye was determined according to two different definitions: at 50% of the maximum contrast sensitivity for each individual eye (relative definition) and at a fixed contrast sensitivity value for all eyes (absolute definition). Spherical aberration was assessed using a Hartmann-Shack wavefront analyzer.

Results

No difference in contrast sensitivity at optimal refractive correction could be found between the two IOLs. With the absolute definition, eyes with the Tecnis IOL yielded a significant smaller depth of focus ($P = .042$) than with the Sensar IOL. A significant relationship between depth of focus and spherical aberration was found for both definitions ($P \leq .01$).

Conclusions

Some spherical aberration seems to be beneficial for the eye's optical performance.

Introduction

Over the years, the wavefront aberrations of the human eye have been studied extensively. This knowledge has contributed to the development of a new intraocular lens (IOL) design with properties more similar to that of the young human lens.¹ This design, the so-called aspheric IOL, reduces the spherical aberration of the eye by correcting for the spherical aberration of the cornea. It has been shown that a reduction in wavefront aberrations such as spherical aberration results in better optical performance. For example, a higher contrast sensitivity has been found in eyes with less spherical aberration.²⁻²⁰

In an aberration-free optical system, a sharp image is produced when an object is correctly focused; with some defocus, image quality decreases rapidly. In an optical system with aberrations, on the other hand, focusing is less critical. Aberrations may compromise image quality when correctly focused but they provide some tolerance for defocus, that is, they increase depth of focus.²¹⁻²³ Depth of focus is the range wherein image quality remains above a certain threshold. A common definition of depth of focus is the range wherein the modulation transfer of an optical system exceeds 50% of the modulation transfer at optimal focus.²⁴

Jansonius and Kooijman have studied the effect of spherical aberration and irregular aberrations on the depth of focus of the human eye using an eye model.²¹ For a pupil diameter of 6.0 mm and a spatial frequency of 8 cycles per degree (cpd), they found a depth of focus of 0.5 D in aberration free optics, 0.7 D in eyes with an average amount of spherical aberration and 1.3 D in eyes with an amount of spherical aberration corresponding to the upper limit of the spherical aberration as found in the human eye, using the definition of depth of focus as mentioned above.

A higher depth of focus in eyes with more spherical aberration, in turn, automatically brings the supposed superiority of aspheric IOLs into question. After all, depth of focus is especially important in eyes that cannot accommodate, such as pseudophakic eyes. It is possible, however, that the apparent poor depth of focus of eyes with little spherical aberration is nothing but an artifact of the definition applied: a higher modulation transfer at optimal focus might result in a lower depth of focus, whereas the modulation transfer value itself remains higher than it does in eyes with more spherical aberration for all defocus values applied. Figure 1 illustrates this paradox. As may be concluded from this figure, a more appropriate comparison of the depth of focus of eyes with different amounts of spherical aberration could possibly be made at an absolute rather than a relative modulation transfer value.

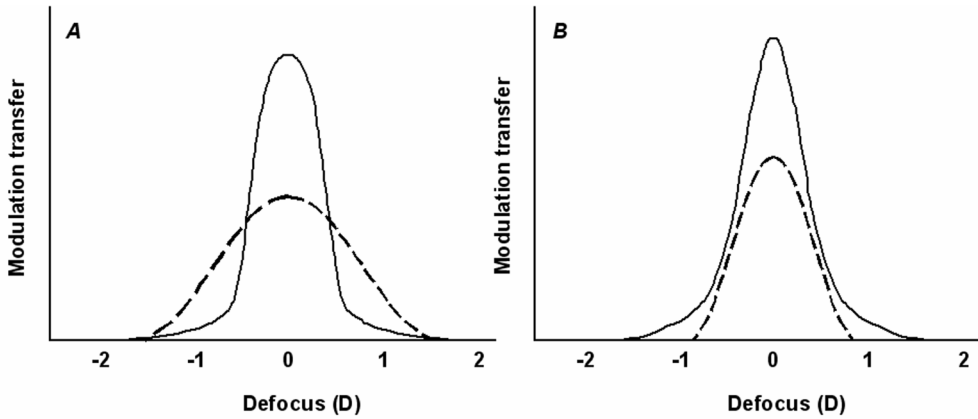


Figure 1. Illustration of the depth-of-focus paradox. **A:** A higher modulation transfer function at optimal focus along with a lower modulation transfer with some defocus resulting in a smaller depth of focus in an eye with little spherical aberration (solid line) as compared to an eye with more aberrations (dashed line). **B:** A smaller depth of focus is also found in this eye with little spherical aberration (solid line) as compared to an eye with more aberrations (dashed line), but now the modulation transfer of the eye with little spherical aberration exceeds that of the eye with more aberrations at all defocus values.

In this study, we compared the depth of focus of eyes with a spherical IOL (Sensar AR40e; Advanced Medical Optics [AMO], Santa Ana, USA) to that of eyes with an aspheric IOL (Tecnis ZA9003; AMO, Santa Ana, USA), using two different definitions of depth of focus (Figure 2): the “relative” definition as proposed by Legge et al.,²⁴ where the depth of focus of an eye is determined at 50% of the maximum contrast sensitivity of the eye itself (full width at half height [FWHH]), and an “absolute” definition, where the depth of focus is compared at the same contrast sensitivity value for all eyes (contrast sensitivity can be used as a proxy for modulation transfer: contrast sensitivity is a composite of the modulation transfer and the sensitivity of the neural part of the visual system; the latter is assumed to be independent of the eye optics). To optimize the comparison, the IOLs were compared within patients (one eye had a spherical IOL and the fellow eye an aspheric IOL). The IOLs used were identical except for the amount of spherical aberration.

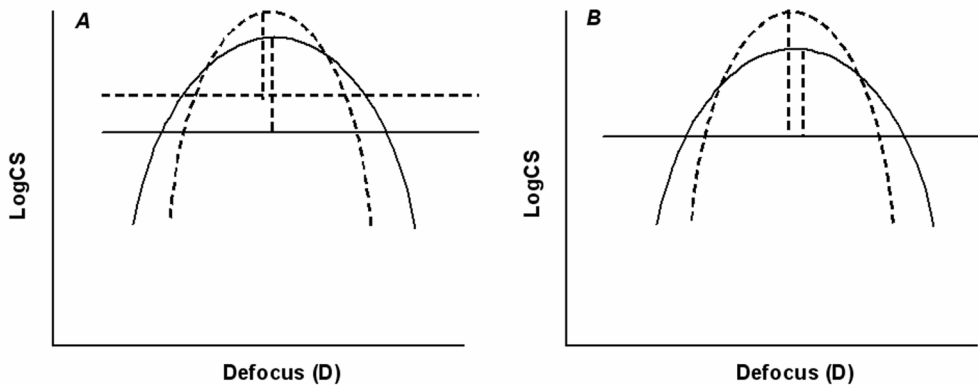


Figure 2. Illustration of the two definitions of depth of focus applied in this study. Dashed lines represent the through-focus curves of an eye with an aspheric IOL; solid lines with a spherical IOL. **A:** The relative definition (FWHH): depth of focus is defined as the dioptric range for which contrast sensitivity exceeds half of its maximum value. **B:** The absolute definition: depth of focus is defined as the dioptric range determined at the contrast sensitivity value for which the eye having the IOL with the higher spherical aberration exceeds half of its maximum value (LogCS = log contrast sensitivity).

Methods

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. The study was registered in the ISRCTN register, Trial Number ISRCTN17058178, and in the Dutch trial registers, Trial Number 813.

Subjects

Thirty-one patients with bilateral age-related cataract were recruited. 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 of more than ± 2 D spherical equivalent in either eye after cataract extraction were excluded, as were eyes 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 a Sensor AR40e IOL (AMO, Santa Ana, USA) in one eye and a Tecnis ZA9003 IOL (AMO, Santa Ana, USA) in the fellow eye. This was randomized with respect to left/right and first/last operated eye. The Tecnis ZA9003 IOL has an aspheric anterior surface. The Sensor AR40e IOL is identical to the Tecnis ZA9003 IOL except that it has a spherical anterior surface.

Biometry was performed with the IOL-Master (Carl Zeiss Meditec AG, Jena, Germany). IOL power was chosen with the aim of an emmetropic postoperative refraction. All surgery was performed by the same experienced surgeon (SK), at the University Medical Center of Groningen, The Netherlands. Implantation in the second eye was scheduled at least one month after the first eye, in accordance with the guidelines of the Dutch Ophthalmic Society.

Contrast sensitivity and spherical aberration measurements

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). After thirty minutes, the pupil size was measured, and then the measurements of the spherical aberration and the contrast sensitivity began. At the time of the measurements, neither the patient nor the investigator was informed regarding which IOL was placed in which eye.

Contrast sensitivity tests were performed under photopic conditions (85 cd/m²) 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, Illinois, USA). Within this test, the circular sine-modulated pattern with a spatial frequency of 6 cpd was used. The test began with 50% contrast. The subject was asked to indicate if the displayed stimulus was a circular pattern or a blank disk. Throughout the test, several blank disks were shown at the same mean luminance level so as to check reliability. After each correct answer, the contrast of the stimulus decreased 0.3 log units. When an incorrect answer was given, contrast increased 0.3 log units (after the second incorrect answer 0.2 log units) and then decreased again, but this time in steps of 0.1 log unit until the next incorrect response. The contrast threshold corresponded to the lowest contrast level at which the subject can identify two out of three circular patterns correctly. Contrast sensitivity was defined as the reciprocal of this contrast threshold and was based on Michelson contrast:

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

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 using optimal refraction for the viewing distance and at several levels of defocus (-2 D, -1 D, and +1 D). The test was performed at a viewing distance of 4 m which is advised for this test.

Wavefront aberrations of the whole eye were measured using a wavefront analyzer (WASCA, version 1.26.3, Asclepion Meditec, Jena, Germany) and presented in standardized Optical Society of America values (micrometers).²⁵ The aberration coefficient c_4^0 belonging to the Zernike polynomial Z_4^0 was used as a measure of spherical aberration and was calculated at an apparent pupil size of 5.0 mm (that is, at a size of 4.5 mm in the WASCA software since the artificial pupil represents the apparent pupil size and the apparent pupil size is about 12% larger than the physical pupil size²⁶ as used in the WASCA software).

Depth of focus

Depth of focus was determined by fitting a parabola through the contrast sensitivity as a function of defocus curve at 6 cpd. To increase accuracy, we required the R^2 of the fitted parabola to be at least 0.85 in both eyes and the highest contrast sensitivity value was not allowed to correspond to either one of the two extreme defocus values (-2 D and +1 D) for either eye. As mentioned in the introduction and shown in Figure 2, depth of focus was determined in two different ways. First, depth of focus was defined as the dioptric range for which contrast sensitivity exceeds half of its maximum value (the relative definition).²⁴ Subsequently, depth of focus of the eyes was determined and compared at the same contrast sensitivity value; the depth of focus of both eyes was calculated at the contrast sensitivity value at which the eye with the Sensor IOL exceeds half of its maximum value in that patient (the absolute definition).

Statistical analysis

The main outcome variable of the contrast sensitivity-test was the logarithmic value of contrast sensitivity (logCS). The t-test for paired samples was used to explore whether a significant difference in spherical aberration and depth of focus between the two IOLs was present; ANOVA (GLM) for repeated measurements was used to identify an interaction within the various defocus levels and between both IOLs. If there was a significant interaction, the t-test for paired samples with Bonferroni correction was used to explore which of the defocus levels were significantly different between both IOLs. The relationship between depth of focus and absolute spherical aberration (aiming at a linear relationship) was calculated with linear regression analysis. To confirm a normal distribution of the residuals, a non-parametric Kolmogorov-Smirnov Z test was performed.

The means are presented with their standard deviation. A P -value ≤ 0.05 was considered statistically significant.

Results

Eleven patients were excluded because the R^2 of the fitted parabola was lower than 0.85 in one or both eyes. One patient was excluded because the through-focus curve of the Tecnis IOL did not surpass the contrast sensitivity value at which the absolute depth of focus had to be calculated. The results from the remaining 19 patients (10 female and 9 male) were included in the analyses. The mean age of these patients was 69 years, with a standard deviation of 12 years and a range from 45 to 87 years. The mean BCVA of eyes with the the Sensor IOL was 102.1 ± 3.0 VAR (range 100 to 110 VAR; Snellen notation 20/20 to 20/12.5; $P = .104$) and of eyes with the Tecnis IOL 101.1 ± 3.6 VAR (range 95 to 105 VAR; Snellen notation 20/25 to 20/16). As was to be expected, a significant difference in spherical aberration could be measured between eyes with the Tecnis IOL (-0.032 ± 0.045 μm) and the Sensor IOL (0.071 ± 0.052 μm ; $P < .001$).

Contrast sensitivity

Figure 3 shows the through-focus curves as measured at 6 cpd for both IOLs. No difference in mean contrast sensitivity at optimal refractive correction could be found between eyes with the Sensor IOL (1.68 ± 0.18) and with the Tecnis IOL (1.73 ± 0.28 ; $P = .37$). With -2 D, however, eyes with the Tecnis IOL resulted in a significantly lower mean contrast sensitivity than eyes with the Sensor IOL ($P = .001$). With -1 D and +1 D defocus, the difference ($P = .015$ and $P = .026$ respectively) between eyes with the Tecnis IOL and Sensor IOL was not statistically significant due to Bonferroni correction.

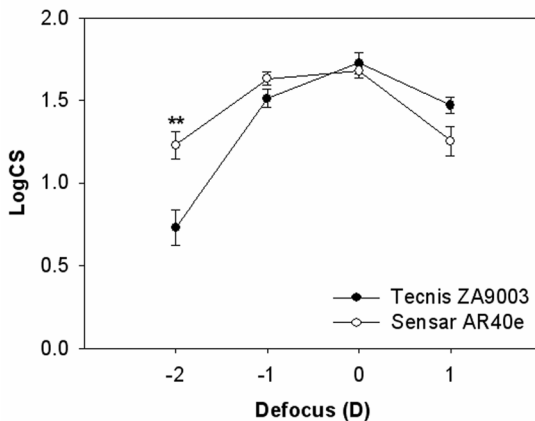


Figure 3. Log contrast sensitivity, measured with an artificial pupil of 5.0 mm, as a function of defocus. Solid circles represent measurements performed on eyes with the Tecnis ZA9003 IOL; open circles on eyes with the Sensor AR40e IOL. Error bars represent the standard error of the mean (LogCS = log contrast sensitivity).

** $P \leq .001$.

Relative and absolute depth of focus

Figure 4 shows the mean depth of focus as measured for both the Tecnis IOL and the Sensor IOL. The relative depth of focus was similar in eyes with the Tecnis IOL (2.41 ± 0.63 D) and eyes with the Sensor IOL (2.67 ± 0.72 D; $P = .15$; Figure 4, A). The mean absolute depth of focus of eyes with the Tecnis IOL (2.37 ± 0.41 D) was significantly lower than that of eyes with the Sensor IOL (2.67 ± 0.72 D; $P = .017$; Figure 4, B).

Figure 5 shows the relationship between depth of focus and the absolute spherical aberration. The slope of the regression line differed significantly from 0 for both definitions of depth of focus (relative depth of focus: slope = 9.2 D/ μm , $R^2 = 0.28$, $P = .001$, Figure 5, A; absolute depth of focus: slope = 6.9 D/ μm , $R^2 = 0.21$, $P = .004$, Figure 5, B).

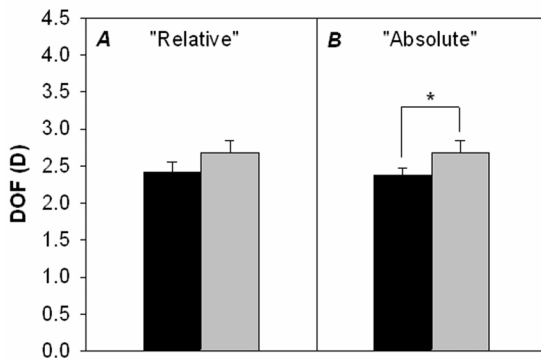


Figure 4. Depth of focus measured with an artificial pupil of 5.0 mm according to the relative definition (A) and the absolute definition (B). Black bars represent measurements performed on eyes with the Tecnis ZA9003 IOL; gray bars on eyes with the Sensor AR40e IOL. Error bars represent the standard error of the mean (DOF = depth of focus). * $P \leq .05$.

Discussion

This study investigated the difference in depth of focus, as measured according to two definitions, between the spherical Sensor AR40e IOL and aspheric Tecnis ZA9003 IOL. No difference in contrast sensitivity at optimal focus between both IOLs could be found. Eyes with the Tecnis IOL had a smaller depth of focus as compared to eyes with the Sensor IOL according to one of the definitions applied.

In the present study, two different definitions to determine the depth of focus were used. We decided to do so because the poor depth of focus found in eyes with little spherical aberration²¹⁻²³ could be an artifact of the definition applied (Figure 1). However, since contrast sensitivity at optimal focus was similar for both IOLs, both definitions should yield similar results. Indeed, the depth of focus comparison according to both definitions showed a similar pattern (Figure 4), although a statistically significant difference was found with only one definition.

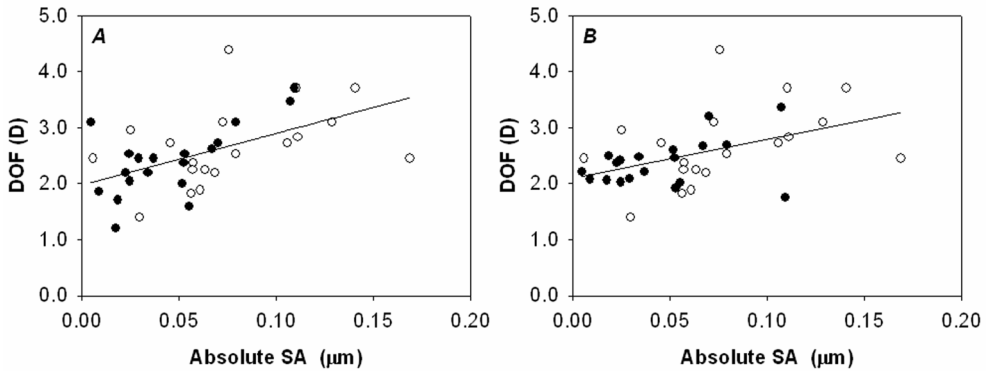


Figure 5. Depth of focus, measured with an artificial pupil of 5.0 mm, as function of absolute spherical aberration according to the relative definition (A) and the absolute definition (B). Solid circles represent measurements performed on eyes with the Tecnis ZA9003 IOL; open circles on eyes with the Sensar AR40e IOL (DOF = depth of focus; SA = spherical aberration).

Marcos and colleagues measured optical modulation transfer functions of eyes with the spherical Acrysof acrylic IOL (Alcon, Ft Worth, Texas) and the aspheric Tecnis Z9000 IOL (AMO).³ The modulation transfer measured at optimal focus was higher for the Tecnis Z9000 IOL than for the Acrysof acrylic IOL. Mean spherical aberration-values of 0.200 μm and -0.086 μm were found for eyes with the Acrysof IOL and Tecnis IOL respectively. Johansson et al. measured contrast sensitivity in patients with the spherical Akreos Adapt AO IOL (Bausch & Lomb, Kingston-upon-Thames, Surrey, United Kingdom) in one eye and the aspheric Tecnis Z9000 IOL in the fellow eye.²⁷ No difference in contrast sensitivity at optimal focus could be found between both IOLs. Mean spherical aberration was 0.05 ± 0.13 μm for eyes with the Tecnis Z9000 IOL and 0.35 ± 0.13 μm for eyes with the Akreos Adapt AO IOL. Marcos et al. and Johansson et al. both defined depth of focus as the dioptric range at which the strehl ratio did not fall below 0.8 times its maximum value.^{3,27} Marcos et al. found a depth of focus of 0.88 D in eyes with the Tecnis Z9000 IOL and of 1.26 D in eyes with the Acrysof IOL,³ and Johansson et al. found a mean depth of focus of 0.86 ± 0.50 D in eyes with the Tecnis Z9000 IOL and of 1.22 ± 0.48 D in eyes with the Akreos Adapt AO IOL.²⁷

The main goal of an aspheric IOL is to reduce the total amount of spherical aberration of the human eye optics^{2-5,7-9,15-18,20,27-32} so as to restore the optical performance.^{2-9,15-20} Both above-mentioned studies showed that the aspheric IOL was able to reduce the

spherical aberration to a close to zero value as compared to the spherical IOL. In our study, however, both the eyes with the Tecnis IOL ($-0.027 \pm 0.044 \mu\text{m}$) and the eyes with the Sensar IOL ($0.071 \pm 0.055 \mu\text{m}$) resulted in a close to zero absolute spherical aberration. This would suggest that the Sensar IOL may not be a truly spherical IOL.

Since the eye that received the Tecnis IOL did not always result in the eye with the smallest spherical aberration, we reorganized the data into two groups; for each patient, the eye that had the lowest absolute spherical aberration was placed in Group I and the eye that had the highest absolute spherical aberration in Group II. This resulted in an average spherical aberration of $-0.004 \pm 0.043 \mu\text{m}$ in Group I and of $0.043 \pm 0.085 \mu\text{m}$ in Group II. Figure 6 shows the through-focus curves as measured at 6 cpd for both groups. No difference in mean contrast sensitivity at optimal focus could be found. When -2D defocus was applied, however, Group I had a significantly lower contrast sensitivity value ($P = .007$).

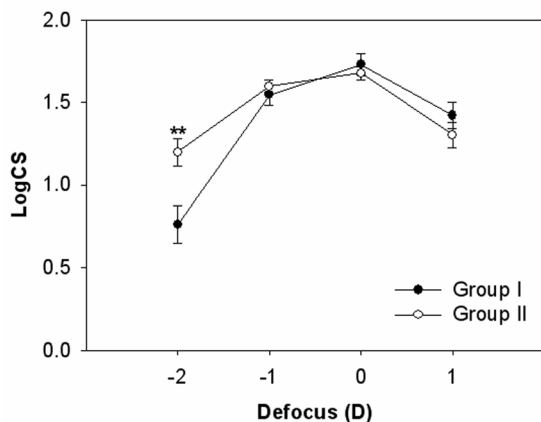


Figure 6. Log contrast sensitivity, measured with an artificial pupil of 5.0 mm, as a function of defocus. Solid circles represent measurements performed on eyes with close to zero spherical aberration (Group I); open circles on the fellow eyes with more spherical aberration (Group II). Error bars represent the standard error of the mean (LogCS = log contrast sensitivity). ** $P \leq .01$.

Figure 7 shows the mean depth of focus for both groups separately. This time the absolute depth of focus was calculated at the contrast sensitivity value at which the eye in Group II exceeds half of its maximum value. A significantly lower mean depth of focus was found in Group I ($2.36 \pm 0.69 \text{ D}$), when calculated following the relative definition but not with the absolute definition ($2.52 \pm 0.76 \text{ D}$), as compared to Group II ($2.72 \pm 0.64 \text{ D}$ and $2.72 \pm 0.64 \text{ D}$, $P = .045$ and $P = .085$; relative and absolute definition respectively). Thus, some spherical aberration is of importance in optical performance: contrast sensitivity at optimal focus did not differ between both IOLs, whereas the depth of focus was lower in eyes with spherical aberration closer to $0 \mu\text{m}$. Too much spherical aberration, however, might compromise contrast sensitivity at optimal focus.³

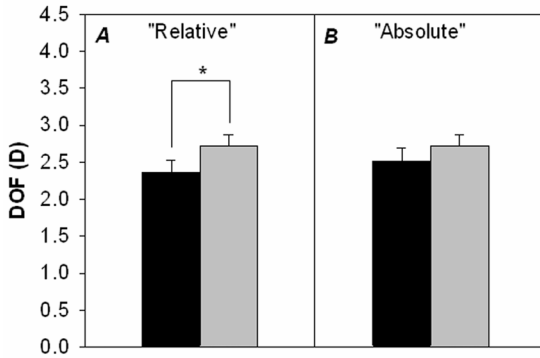


Figure 7. Depth of focus, measured with an artificial pupil of 5.0 mm, according to the relative definition (A) and the absolute definition (B). Black bars represent Group I (eyes with the fewer spherical aberration); gray bars Group II (fellow eyes with larger spherical aberration). Error bars represent the standard error of the mean (DOF = depth of focus).

In conclusion, it seems preferable to have some residual spherical aberration in the human eye optics. IOLs might well be chosen using knowledge of the corneal spherical aberration of individual patients: patients with a small amount of corneal spherical aberration might benefit from a conventional spherical IOL, patients with an average amount of corneal spherical aberration might be better off with a Sensar-like design, whereas the use of an aspheric IOL should be limited to those patients with a more than average corneal spherical aberration. Generally speaking, the differences between the Sensar IOL and Tecnis IOL remain relatively small.

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