Impact of Decentration and Tilt on Spherical, Aberration Correcting, and Specific Aspherical Intraocular Lenses: An Optical Bench Analysis

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Keywords

Optical bench · Decentration · Tilt · Monofocal IOL · Quality of vision

Abstract

Introduction: The human eye is not optically symmetrical, and very few intraocular lens (IOLs) are perfectly centered in the eye. That is why contrast sensitivity can degrade in some conditions, especially in low light. In an optical bench analysis, we compare spherical (A), aberration correcting (B), and specific aspherical lenses (C) in terms of impact of decentration and tilt on the modulation transfer function as well as the simulated overall quality with USAF test targets. **Material and Methods:** The OptiSpheric IOL PRO2 was used to measure the optical performance of IOLs (A, B, C). In order to assess the optical quality of the IOLs, the optical quality parameters for the aperture size of 3.0 mm and 4.5 mm at the IOL plane were assessed. Through Frequency Modulation Transfer Function (MTF) and Strehl Ratio (SR) values, as well as the “US Airforce 1951 resolution test chart images” as qualitative simulation, were analyzed. All measurements (ISO) were repeated and done for centered, decentered (1 mm), and tilted (5°) IOLs. **Results:** Centered: The MTF (mean)

at 50 lp/mm (IOL A, B, C) with 3.0-mm aperture was 0.794/0.716/0.797 (ISO-1 cornea) and 0.673/0.752/0.723 (ISO-2 cornea) and with 4.5-mm aperture 0.728/0.365/0.751 (ISO 1) and 0.276/0.767/0.505 (ISO 2). The SR (mean) with 3.0-mm aperture was 0.763/0.829/0.898 and with 4.5-mm aperture 0.228/0.386/0.432. Decentered by 1 mm: The MTF (mean) at 50 lp/mm with 3.0-mm aperture was 0.779/0.459/0.726 (ISO 1) and 0.695/0.381/0.662 (ISO 2). The MTF (mean) at 50 lp/mm with 4.5-mm aperture was 0.732/0.348/0.653 (ISO 1) and 0.355/0.069/0.346 (ISO 2). The SR (mean) with 3.0-mm aperture was 0.829/0.543/0.397 and with 4.5-mm aperture was 0.259/0.145/0.192. Tilted by 5°: The MTF (mean) at 50 lp/mm with 3.0-mm aperture was 0.731/0.705/0.751 (ISO 1) and 0.623/0.727/0.732 (ISO 2). The MTF (mean) at 50 lp/mm with 4.5-mm aperture was 0.579/0.406/0.701 (ISO 1) and 0.277/0.512/0.429 (ISO 2). The SR (mean) with 3.0-mm aperture was 0.539/0.478/0.514 and with 4.5-mm aperture was 0.262/0.136/0.201. **Conclusion:** Aberration correcting IOLs perform best when perfectly centered. The optical performance of aberration correcting IOLs can be markedly downgraded by misalignment. The examined ZO optic performed well in decentration and tilt. The ZO concept seems to be a good alternative to aspheric lenses, as it achieves to combine benefits of spherical and aspheric

intraocular lenses. There is no perfect IOL, but fitting and choosing the right one for the individual case seems to be crucial to take advantage of benefits and minimize disadvantages. This is why knowledge of optical properties is also mandatory for the surgeon.

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Introduction

In Market Scope and in the annual intraocular lens (IOL) Report, it is estimated that 34 million cataract surgeries are performed worldwide in 2021. Monofocal lenses are implanted in >90% of the cases, and only in 10% of the cases, so-called premium intraocular lenses (toric, multifocal, enhanced depth of focus) are used. Among the monofocal lenses, the one-piece, hydrophobic acrylic lenses are the most common. A detailed analysis of the optics of these monofocal lenses is therefore crucial, as it involves more than 30 million lens implants per year.

In spherical aberration (SA), rays of light do not all meet at the same image point. Rays passing through the lens close to its center are focused farther away than rays passing through a circular zone near its rim. As a result, there is a marginal ray focus and a paraxial ray focus with longitudinal and transverse SA. In the human eye, the crystalline lens ages and its positive SA increases. This causes an increase in total optical system aberration. Implanting a standard spherical IOL in cataract surgery increases that SA further. Nowadays, surgeons have the choice between different types of monofocal IOLs with different asphericities. Each category has advantages and disadvantages, which should be considered.

It was already shown that aspheric IOLs achieve better contrast sensitivity compared to spherical IOLs at mesopic and scotopic conditions with equal visual acuity [1–3]. In intraindividual comparisons, there were no statistically significant differences between spherical and aspheric IOL in visual acuity measurements or contrast sensitivity measurements. Although primary SA Z(4)(0) was significantly lower in the eyes with the aspherical IOL, no statistically significant differences were found between aspherical and spherical IOLs in low contrast visual acuity and high contrast visual acuity. Statistical analysis of intraindividual contrast sensitivity differences showed that in most patients, this Z(4)(0) difference was too low to have an effect on contrast sensitivity [4]. In comparison to a spherical IOL, aspherical IOLs reduced Z(4)(0) and 4th order RMS significantly for pupil diameters of 3–6 mm, whereas total HOA RMS was only sig-

nificantly reduced for a pupil diameter of 6 mm [5]. In a systematic review article and summary of the impact on vision of an aspheric IOL compared with a spherical IOL in cataract surgery, authors concluded that a patient may achieve better contrast sensitivity with an aspheric IOL than with a spherical IOL, especially under dim light, but there was no clinically relevant difference in BCVA between aspheric and spherical IOL implantation. The findings on the subjective perception of visual quality were heterogeneous with no clear result favoring either option [6]. Spherical IOLs create positive SAs in addition to the positive corneal SA. If the optic position is not well aligned, other higher order aberrations, such as coma, may occur, which can affect quality of vision.

Asphericity-neutral IOLs do not create any SAs: they are suitable for all patients regardless of their cornea shape. They are not sensitive to decentration and tilt. But they do not correct positive corneal SA, so there is some loss of contrast.

Aberration correcting IOLs are designed to offset the positive SA of an average cornea. The average corneal asphericity is supposed to be 0.27μ as reported in literature by most of the authors. Aberration correcting IOLs can thus improve contrast sensitivity particularly when the pupil diameter is large. If the optic position is misaligned, higher order aberrations, such as coma, could occur, which can affect quality of vision considerably – even to a larger extent compared to spherical IOLs.

Aspheric ZO optic IOLs (patented aspheric “ZEISS Optics”[®]) are designed to compensate for a range of aberrations arising from different corneal asphericities and lens misalignments. The optic design aims to make the lens less sensitive to decentration and tilt. As a result, the ZO optics should provide better image quality in real-life.

The typical human eye is not optically symmetrical, and very few IOLs are perfectly centered in the eye even after a standard, routine surgery without any complication. In a validation study comparing Purkinje and Scheimpflug imaging, IOLs tended to be tilted and decentered nasally in most patients [7].

That is why contrast sensitivity can degrade in some conditions, especially in low light. Studies showed that the effect of IOL displacement on visual function is more pronounced in aberration correcting IOLs compared to spherical and standard nonaberration correcting aspherical IOLs [8]. It is well known that aspherical IOLs are more sensitive than spherical IOLs to misalignment or tilt, depending on their SA correction. The optical degradation caused by IOL misalignment has greater effect on IOL designs with a higher amount of negative SA [9, 10].

Tilt and decentration of intraocular lenses may occur secondary to a complicated cataract surgery or following an uneventful phacoemulsification. Although up to 2–3° tilt and a 0.2–0.3 mm decentration are common and clinically unnoticed for any design of IOL, larger extent of tilt (>3°) and decentration (>0.3 mm) has a negative impact on the optical performance and subsequently, the patients' satisfaction [11–13]. IOL misalignment and angle κ have a significant negative impact on postoperative quality of vision, regarding to a study that used ZEMAX software to imitate the optical performance of pseudophakic eyes with different IOL surface designs at different orientations of IOL misalignment (decentration of 0.4 mm and tilt of 7°, and with the existence of 0.5 mm angle κ) [14]. In an optical bench analysis, we compared spherical, aberration correcting, and specific aspherical IOLs in terms of impact of decentration and tilt on the modulation transfer function and Strehl values with different sizes of aperture, as well as measuring the simulated overall quality with USAF test targets.

Methods

Optical Bench

The OptiSpheric IOL PRO2 (Trioptics GmbH, Wedel, Germany) was used to measure the optical performance of the IOLs, which follows the guidelines of the International Standard Organization. The OptiSpheric IOL PRO2 derives the optical quality parameters (modulation transfer function [MTF]) from the Fourier transform of the line spread function projected by the lens under test. The MTF components were assessed using a spectral filter that simulates the photopic luminosity function established by the Commission Internationale de l'Éclairage.

Measurements were carried out using two in situ eye models with NaCl ($n = 1.337$), heated to 36°C to simulate the human eye. IOLs were tested with two different corneas, the ISO-1 cornea without SA and the ISO-2 cornea with a positive asphericity of 0.28 μ (ISO 11979/2 and ISO 11979-2). Apertures of 3 mm (ISO-standard) and 4.5 mm were applied to simulate a photopic and a mesopic pupil.

MTF and Strehl Ratio

In order to assess the optical quality of the IOLs, the optical quality parameters for the aperture size of 3.0 mm and 4.5 mm at the IOL plane were assessed. Through Frequency Modulation Transfer Function and Strehl ratio (SR) values, as well as the "US Airforce 1951 resolution test chart images" as qualitative simulation, were analyzed. We used MTF tan and MTF sag values to calculate the mean value. Since the SR accounts for all small oscillations that occur on the Through Frequency MTF curve, it can reflect the overall optical performance. All measurements were done for centered, decentered (1 mm), and tilted (5°) IOLs. Each value of MTF consisted of 5 single measurements, and hence, the mean values were calculated out of 10 single measurements.

USAF 1951 Resolution Test Chart

We used in situ measurement conditions (NaCl, 36°C, ISO-2 cornea) to evaluate "US Air Force 1951 resolution test chart images." USAF targets to simulate contrast visual acuity were evaluated at best focus by a gradient scan. Shutter time was automatically adjusted.

Intraocular Lenses

We assessed three acrylic, hydrophobic, monofocal IOLs, each having the same nominal power of +22.0 D. IOL A: Sensor (Johnson & Johnson Vision, Santa Ana, CA, USA) is a hydrophobic, single-piece acrylic IOL with an overall diameter of 13.0 mm and an optical diameter of 6.0 mm with a classic C-loop design. The UV-blocking, hydrophobic material has a refractive index of 1.47 and a typical spherical design.

IOL B: Tecnis Monofocal 1-Piece (Johnson & Johnson Vision, Santa Ana, CA, USA) is a hydrophobic, single-piece acrylic IOL with an overall diameter of 13.0 mm and an optical diameter of 6.0 mm with a classic C-loop design. The UV-blocking, hydrophobic acrylic material has a refractive index of 1.47 at 35°C and an Abbe number of 55. The aspheric design of the Tecnis corrects -0.27μ of primary SA to improve contrast sensitivity. It is designed to reduce chromatic aberration.

IOL C: CT Lucia 621P (Carl Zeiss Meditec, Jena, Germany) is a hydrophobic, single-piece acrylic, heparin-coated IOL with a diameter of 13.0 mm and an optical diameter of 6.0 mm with a classic C-loop design. The aspheric design of the Lucia corrects -0.12μ of primary SA. The patented ZO optic (Carl Zeiss Meditec) is designed on the basis of the Liou-Brennan eye model to compensate for a range of aberrations arising from different corneal curvature and lens misalignments. It is optimized for a pupil size of 4–5 mm, typically found in cataract patients. The optic has a central zone with negative SA to balance corneal aberration for an improved image quality and a peripheral zone with positive SA to increase tolerance toward decentration. The optic design thus is supposed to combine benefits of aberration correcting and aberration-neutral IOLs.

It should be emphasized here that all 3 types of lenses (A, B, and C) have been implanted very successfully for many years and contribute to high patient satisfaction. This has been proven by various studies in the past.

Statistics

For the statistical evaluation of MTF and SR, an analysis of variance was performed with the factors IOL, mode and aperture, and all interactions to degree two. As post hoc test a Tukey test was used. The significance level was set to 0.05. The analysis was done with R version 3.6.1.

Results

Optical-Quality Assessment

The through frequency MTF of all IOLs measured at the best focus through the 3.0 mm (Fig. 1–3) and 4.5 mm (Fig. 4–6) apertures are presented.

Centered: The MTF (mean) at 50 lp/mm (IOL A, B, C) with 3.0-mm aperture and ISO-1 cornea was

Fig. 1. MTF values with 3.0-mm aperture and centered IOLs (x axis: spatial frequency [lp/mm] and y axis: MTF [sag, tan]).

Fig. 2. MTF values with 3.0-mm aperture and decentered IOLs (x axis: spatial frequency [lp/mm] and y axis: MTF [sag, tan]).

Fig. 3. MTF values with 3.0-mm aperture and tilted IOLs (x axis: spatial frequency [lp/mm] and y axis: MTF [sag, tan]).

Fig. 4. MTF values with 4.5-mm aperture and centered IOLs (x axis: spatial frequency [lp/mm] and y axis: MTF [sag, tan]).

Fig. 5. MTF values with 4.5-mm aperture and decentered IOLs (x axis: spatial frequency [lp/mm] and y axis: MTF [sag, tan]).

Fig. 6. MTF values with 4.5-mm aperture and tilted IOLs (x axis: spatial frequency [lp/mm] and y axis: MTF [sag, tan]).

Fig. 7. Aperture shift with 3.0-mm aperture (x axis: spatial frequency [lp/mm] and y axis: MTF [sag, tan]).

Table 1. All MTF mean values with ISO-1 and ISO-2 cornea and SR for centered, decentered, and tilted lenses with 3.0-mm and 4.5-mm aperture

	MTF mean (50 lp/mm) ISO-1 cornea	MTF mean (50 lp/mm) ISO-2 cornea	SR		MTF mean (50 lp/mm) ISO-1 cornea	MTF mean (50 lp/mm) ISO-2 cornea	SR
3 mm centered				4.5 mm centered			
IOL A	0.794	0.673	0.763	IOL A	0.728	0.276	0.228
IOL B	0.716	0.752	0.829	IOL B	0.365	0.767	0.386
IOL C	0.797	0.723	0.898	IOL C	0.751	0.505	0.432
3 mm decentered				4.5 mm decentered			
IOL A	0.779	0.695	0.829	IOL A	0.732	0.355	0.259
IOL B	0.459	0.381	0.543	IOL B	0.348	0.069	0.145
IOL C	0.726	0.662	0.397	IOL C	0.653	0.346	0.192
3 mm tilted				4.5 mm tilted			
IOL A	0.731	0.623	0.539	IOL A	0.579	0.277	0.262
IOL B	0.705	0.727	0.478	IOL B	0.406	0.512	0.136
IOL C	0.751	0.732	0.514	IOL C	0.701	0.429	0.201

Fig. 8. Aperture shift with 4.5-mm aperture (x axis: spatial frequency [lp/mm] and y axis: MTF [sag, tan]).

0.794/0.716/0.797 and with ISO-2 cornea was 0.673/0.752/0.723. The MTF (mean) at 50 lp/mm (IOL A, B, C) with 4.5-mm aperture and ISO-1 cornea was 0.728/0.365/0.751 and with ISO-2 cornea was 0.276/0.767/0.505. The SR (mean) with 3.0-mm aperture (IOL A, B, C) was 0.763/0.829/0.898 and with 4.5-mm aperture 0.228/0.386/0.432.

Decentered by 1 mm: The MTF (mean) at 50 lp/mm (IOL A, B, C) with 3.0-mm aperture and ISO-1 cornea was 0.779/0.459/0.726 and with ISO-2 cornea was 0.695/0.381/0.662. The MTF (mean) at 50 lp/mm (IOL A, B, C) with 4.5-mm aperture and ISO-1 cornea was 0.732/0.348/0.653 and with ISO-2 cornea was 0.355/0.069/0.346. The SR (mean) with 3.0-mm aperture (IOL A, B, C) was 0.829/0.543/0.397 and with 4.5-mm aperture was 0.259/0.145/0.192.

Tilted by 5°: The MTF (mean) at 50 lp/mm (IOL A, B, C) with 3.0-mm aperture and ISO-1 cornea was 0.731/0.705/0.751 and with ISO-2 cornea was 0.623/0.727/0.732. The MTF (mean) at 50 lp/mm (IOL A,

B, C) with 4.5-mm aperture and ISO-1 cornea was 0.579/0.406/0.701 and with ISO-2 cornea was 0.277/0.512/0.429. The SR (mean) with 3.0-mm aperture (IOL A, B, C) was 0.539/0.478/0.514 and with 4.5-mm aperture 0.262/0.136/0.201.

Measured Strehl findings were in accordance to MTF results. This indicates, with certain limits, corresponding expected retinal image quality (Table 1). Figures 7 and 8 shows the aperture shifts of 3.0 and 4.5 mm and the different effects on the lenses.

USAF Test Charts

The simulated visual function using USAF test targets showed partly corresponding qualitative results. Differences in brightness, halos, and ghosting were recorded between the lenses. An auto-shutter had been used for the assessment of all IOLs (Fig. 9–12).

Fig. 9. USAF results with 3.0-mm aperture and centered IOLs.

Fig. 10 USAF results with 3.0-mm aperture and tilted IOLs and aperture shift.

Fig. 11. USAF results with 4.5-mm aperture and centered/decentered IOLs.

Fig. 12. USAF results with 4.5-mm tilted IOLs and aperture shift.

Discussion

It is well known that the optical performance of an IOL on the optical bench is depending on the model cornea used. The goal is the best MTF at a frequency to be determined, mostly 50 lp/mm and 100 lp/mm. Each manufacturer is using its own corneal model to develop its own specific IOL, depending on the manufacturer's philosophy. However, it is evident that a lens cannot achieve "high performance" under all possible conditions. Therefore, we believe it is important to evaluate lenses on the optical bench under different conditions. We have used ISO-1 and ISO-2 model corneas to receive objective and comparable results and show differences. In our opinion, it is very important to evaluate the findings from this aspect. We believe that only a comparison of measurements at ISO 1 and ISO 2 gives a good overall view, otherwise wrong conclusions could be drawn. Moreover, this knowledge is important for the best possible choice in the individual case.

Centration of the IOL is an important factor that is more of an issue with aberration correcting lenses. Standard IOLs, which add positive SA to the optical system, do not create major problems if they decenter. However, a lens designed to have negative aberration is a different matter. Zero SA or aberration-neutral means that the power of that lens is the same throughout its complete optics. The advantage of a lens with zero SA is that if it is decentered it is not interfering any existing aberrations. So, if there is a risk factor that the lens may decenter after implantation because of zonular weakness, pseudoexfoliation or in traumatic surgery, IOLs with zero SA should be the first choice.

New aspheric optics like the CT Lucia 621P are designed to compensate for a range of aberrations arising from different corneal curvatures and lens misalignments. As a result, it should provide better imaging quality for real-life conditions. Moreover, it is less sensitive in cases of decentration and tilt.

In real life, many patients with good visual acuity will not notice the minor difference between different aspherical IOLs. Under mesopic conditions, such as driving in twilight, a patient with large pupils could notice such differences more likely. It is also well known that the power of the implant plays an important role; in hyperopic cases, the standard spherical lens with +30 D power would induce far more positive SA than the +15 D implant in myopic cases. Therefore, using an aspheric lens would probably make a noticeable difference in these cases. As asphericity is pupil-dependent and cataract patients getting younger at the time of surgery nowadays, the issue of

asphericity in different pupil sizes is becoming more and more important. A 55-year-old patient, who is driving at night with larger pupils may notice some loss of contrast while a 85 years old may not notice it. Many clinical evaluations have shown that lower order aberrations (sphere and cylinder) have a greater impact than higher order aberrations such as SA. It is also known that patients benefit from an emmetropic eye with any IOL (without refractive error) much more than having an aspheric IOL but higher amounts of residual refractive errors. There are many other factors such as refractive index, Abbe number, clarity of the material and transmission spectrum that have an impact on the overall results.

Sometimes surgeons may consider if aspheric lenses have benefits and outweigh the extra cost and extra time of measurements prior to surgery. Many studies are suggesting that there is often very little noticeable difference between a spherical and an aspheric lens from the patient's perspective. And as a matter of fact, a lot of people have done very well with standard spherical lenses for many years. On the other side, benefits of an aberration correcting lens regarding contrast sensitivity have been proven. If an IOL is misaligned after surgery, an aberration correcting IOL will have similar low contrast sensitivity compared to a spherical IOL. While the relative decrease of contrast sensitivity is more pronounced for that aberration correcting IOL, the performance will be very close to the decreased performance of a spherical IOL, especially for larger pupils. This relationship could be shown and proved on the optical bench in our settings, too. The complex and unique ZO optic® seems to combine both features, a larger contrast sensitivity in relation to the spherical lens and less relative loss of contrast when being misaligned.

Conclusion

This laboratory study is not suitable to make a rating of the IOLs (A, B, C) and to determine a better and a worse lens. The aim of this study was to present the optical properties, to show differences with advantages and disadvantages, and to analyze the influence of decentration and tilt. We believe that it is the surgeon's responsibility to know these facts as well in order to make the right choice in the individual case.

Aberration correcting IOLs perform best when perfectly centered. There is minor loss of contrast with larger apertures compared to spherical IOLs. Misalignment can markedly deteriorate the optical performance of aberration cor-

recting IOLs. Therefore, we believe that it should be considered in patient selection as there are a few possibilities (anatomical, secondary diagnoses, surgical factors) that can increase the probability of decentration or tilt.

The ZO optic showed good results and performed well in decentration and tilt. The ZO concept seems to be a good alternative to aspheric lenses, as it achieves to combine benefits of spherical and aspheric intraocular lenses.

Statements of Ethics

The paper is exempt from ethical committee approval, as it is an optical bench analysis (in vitro study) without humans involved.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

The optical bench analysis is part of the collaboration project (GRUL 20/20) of German and Austrian refractive surgeons (A.F.B., R.S.) to evaluate lens designs. All measurements were performed by Trioptics (Wedel, Germany) with its own optical bench, and the validity of the data was confirmed by certificates.

Data Availability Statement

All data generated or analyzed during this study are included in this article. Further enquiries can be directed to the corresponding author.