Outcomes of Corneal Spherical Aberration-guided Cataract Surgery Measured by the OPD-Scan

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ABSTRACT
PURPOSE: To determine based on preoperative corneal spherical aberration, the practicality of targeting zero total ocular postoperative spherical aberration when selecting an aspheric intraocular lens (IOL).

METHODS: Consecutive cataract patients were selected to receive an aspheric IOL based on corneal spherical aberration. A target of zero postoperative total spherical aberration Z(4,0) was calculated. One of three IOLs was chosen, based on the corneal spherical aberration Z(4,0) measurement at the 6-mm optical zone. The IOL was selected based on the summation of the corneal spherical aberration and the aspheric value of the prolate optic. The intention was an absolute value of zero total spherical aberration. Statistical analysis of the postoperative total ocular wavefront profile was performed to assess the accuracy of aspheric IOL selection.

RESULTS: Forty eyes of 40 patients were available for postoperative assessment. The Tecnis Z9003 (Abbott Medical Optics) was implanted in 25 eyes with a preoperative corneal spherical aberration of $0.311 \pm 0.054 \mu m$, the AcrySof IQ (Alcon Laboratories Inc) in 13 eyes ($0.188 \pm 0.034 \mu m$), and the SofPort-Advanced Optic with Violet Shield (Bausch & Lomb) was implanted in 2 eyes ($0.0915 \mu m$). Total postoperative ocular spherical aberration for the entire group measured $0.019 \pm 0.051 \mu m$ (Tecnis: $0.024 \pm 0.058 \mu m$; AcrySof IQ: $0.010 \pm 0.035 \mu m$; and SofPort AOV: $0.037 \mu m$). Mean absolute predictive error, for the entire group, measured $0.025 \pm 0.020 \mu m$.

CONCLUSIONS: Skiascopy-derived total wavefront measurement of spherical aberration is a reproducible method of aspheric IOL selection and permits more precise control of total ocular spherical aberration. [J Refract Surg. 2010;xxx;xxx-xxx.]
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Once a procedure solely devoted to the safe removal of a cataract, contemporary microincisional phacoemulsification and intraocular lens (IOL) implantation has developed into lens-based refractive surgery for those who have developed visually significant cataracts. As a result, increasing visual demands require the surgeon to achieve greater control of refractive outcomes and ultimately more precise visual enhancement.

Numerous studies have demonstrated the change in optical aberration in the aging eye. The development of wavefront sensors has made it possible to identify otherwise unquantifiable refractive measures. The study of wavefront optics has led to the creation of aspheric IOLs, specifically designed to mitigate the naturally occurring positive spherical aberration of the cornea. Clinical studies comparing aspheric implants with spheric implants have found that modified prolate optics significantly improve contrast sensitivity under mesopic conditions.

This increased knowledge has led to the management of spherical aberration in the cornea and is the basis for the US Food and Drug Administration (FDA) designating New Technology IOL (NTIOL) status on four aspheric IOLs. Despite disagreement as to the absolute value, studies suggest that reduction of total ocular spherical aberration is optimal when approaching emmetropia. Measuring 696 eyes, Beiko et al reported a normal Gaussian distribution of corneal spherical aberration. The mean spherical aberration across a 6.0-mm pupil was $\pm 0.274 \pm 0.089 \mu m$ and is consistent with previously reported values in a study by Holladay et al. Therefore, the Tecnis Z9003 IOL (Abbott Medical Optics, Santa Ana, Calif), the first aspheric lens granted NTIOL status, induces negative spherical aberration of 0.27 µm through...
a modified anterior prolate surface, whereas the AcrySof SN60WF IOL (Alcon Laboratories Inc, Ft Worth, Tex) provides 0.20 µm of negative spherical aberration with a blue-light filtering chromophore and a posterior prolate surface. Consequently, with decreasing dioptric power from center to edge, centration of aspheric optics becomes critically important. Subsequent studies have shown an exaggeration of both lower and higher order aberration with as little as 0.5 to 1.0 mm of displacement from the visual axis.15,16 Bausch & Lomb, therefore, created an IOL with zero spherical aberration. The SofPort Advanced Optic with Violet Shield IOL (LI61AOV; Bausch & Lomb, Rochester, NY) combines an ultraviolet and violet-light filtering chromophore to a biprolate, silicone optic that is aspherically neutral, and therefore will not add or subtract from pre-existing higher order aberrations. The SofPort lens has a uniform thickness and refractive power resisting the refractive effect of decentration, even when displaced as much as 1.0 mm.16

A growing clinical interest in waveform profiles creates a strong commercial interest in making aberrometry a part of daily clinical practice. Currently, instruments used for the determination of ocular waveform aberration are designed to measure focal shift—the principle that an aberrated lens refracts an incident beam of light in front or behind the expected focal point, given a perfect optical system, resulting in a shift of the refracted beam with respect to the focal plane.

Practical comparison between the available aberrometers is difficult due to the variety of principles used, such as Hartmann-Shack, Tscherning, ray tracing, and automatic retinoscopy. The ARK-10000 (OPD-Scan; NIDEK Co Ltd, Gamagori, Japan) uses the principle of dynamic skiascopy and is the only manufacturer of this type of waveform sensor for clinical purposes. As a serial, double-pass aberrometer, an infrared light slit and photodetectors are placed on a rotating wheel along the same rotational position across the pupil. Moving the incident beam along a specific pupillary meridian results in a reflected beam that will go in the same or opposite direction. As the wheel is rotated, the instrument then compares the time it takes for light to peak at each photodiode after passing a beam splitter. The device calculates the optical pathway difference and derives the waveform error by comparing the results with the theoretical reference time and generates a refractive map and waveform profile. This procedure yields 1440 data points within 0.4 seconds.17,19

The intention of the current study is to determine the feasibility of targeting a total ocular spherical aberration of zero, utilizing the current cache of aspheric IOLs, based on the calculated preoperative corneal spherical aberration and measured total ocular spherical aberration with the OPD-Scan.

**PATIENTS AND METHODS**

This prospective study comprised 40 eyes of 40 consecutive patients (23 men and 17 women) with age-related visually significant cataracts, unsatisfactorily corrected with spectacles, who desired visual improvement. Patients were excluded if any of the following conditions were present: existing pathology that would limit visual acuity or potentially compromise centration of the implant (ie, amblyopia, diabetic retinopathy, macular degeneration, glaucoma, history of uveitis, pseudoexfoliation syndrome), previous keratorefractive surgery, pupil dilation of <6.0 mm (with or without pharmacologic mydriasis), >1.0 diopters (D) of corneal astigmatism that would warrant correction, and potential visual acuity worse than 20/25.

Preoperatively, each patient was evaluated with corrected distance visual acuity (CDVA) and detailed slit-lamp microscopic examination with applanation tonometry, which followed manual keratometry. Biometry, anterior chamber depth, and corneal white-to-white measurements were obtained with the IOLMaster (Carl Zeiss Meditec Inc, Dublin, Calif) along with lens power calculations performed with the SRK-T formula. Preoperative corneal topography was acquired through an integrated Placido image and the corneal spherical aberration Z(4,0) is derived from the sixth order Zernike expansion generated from the refractive map. Near simultaneous measurement of total ocular spherical aberration Z(4,0) was reconstructed at the 6.0-mm optical zone transposed to the corneal vertex. All measurements were performed with interphase software analysis on the OPD-Scan version 2.11.04.

With the intent of achieving total ocular spherical aberration of zero, the lens selection was based on preoperative corneal spherical aberration. Consequently, the Tecnis Z9003 was the lens of choice for corneal spherical aberration of $>+0.235$ µm, whereas the LI61AOV was selected for corneal spherical aberration $<+0.10$ µm. For eyes with corneal spherical aberration $>+0.10$ µm and $<+0.235$ µm, the AcrySof IQ SN60WF was selected.

All surgical procedures were performed by the same surgeon (J.D.S.) using the Infinity (Alcon Laboratories Inc) phacoemulsification machine. Perioperative treatment included diclofenac (Voltaren; Novartis, E Hanover, NJ) and moxifloxacin (Vigamox, Alcon Laboratories Inc). After topical anesthesia, surgery was performed through a 2.75-mm, self-sealing, on-axis, clear corneal incision and 1.0-mm paracentesis at 90° from the main incision. Following anterior chamber
### TABLE

**Aspheric IOLs Implanted in 40 Eyes After Cataract Surgery**

<table>
<thead>
<tr>
<th>Aspheric IOL</th>
<th>IOL Selection</th>
<th>Age (y)</th>
<th>No. Eyes (F:M)</th>
<th>Preop Corneal Z(4,0) µm</th>
<th>Postop Ocular* Z(4,0) µm</th>
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<tbody>
<tr>
<td>Tecnis</td>
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<td>Manufacturer</td>
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<td>Chromophore</td>
<td>UV blocking</td>
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<td>Design</td>
<td>Three-piece</td>
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<td>Optic size (mm)</td>
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<tr>
<td>Material</td>
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<td>AcrySof IQ</td>
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<td>Spherical aberation (µm)</td>
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<tr>
<td>Chromophore</td>
<td>Blue-light filter</td>
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<td>Material</td>
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<td>Manufacturer</td>
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<tr>
<td>Chromophore</td>
<td>UV &amp; violet blocking</td>
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<td>Material</td>
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*Total ocular spherical aberration was measured with a 6-mm pupil at 4 weeks postoperatively.

*Table 1 (continued on next page)*
inflation of an ophthalmic viscosurgical device, a capsulorrhesis of 5.5 mm in diameter was created. Hydrodissection and hydrodelineation allowed for uneventful phacoemulsification and irrigation/aspiration. The IOL was implanted and centered in the bag followed by gentle hydration of the corneal incisions.

Four weeks postoperatively, a thorough ophthalmic examination was performed, which included CDVA and repeat OPD-Scan with pupillometry, topography, and a dilated measurement of corneal spherical aberration and total ocular spherical aberration for a 6.0-mm pupil. Predicted spherical aberration based on the summation of the preoperative corneal spherical aberration and the labeled spherical aberration of the implanted IOL, was compared to the measured total ocular spherical aberration at a 6.0-mm pupil.

RESULTS

Of the 40 consecutive patients, mean preoperative spherical equivalent refraction was −1.19±2.44 D, and the preoperative corneal spherical aberration measured at a 6.0-mm pupil was 0.260±0.084 µm for the entire study group (Table, Fig 1). As a result, 25 eyes were selected to receive the Tecnis IOL and therefore had corneal spherical aberration of >0.235 µm with a mean spherical aberration of 0.311±0.054 µm, whereas 13 eyes had Z(4,0) between 0.1 and 0.235 µm and received the AcrySof SN60WF with a mean of 0.188±0.034 µm. Two study patients had corneal spherical aberration <0.1 µm and were implanted with the neutral aspheric L161AOV. The first patient’s right eye measured +0.098 µm of corneal spherical aberration, and the second patient, also a right eye, measured +0.085 µm.

Postoperative mean spherical equivalent refraction for the entire group was −0.13±0.33 D, with total ocular spherical aberration of 0.019±0.051 µm when measured for a 6.0-mm pupil. The two eyes with the L161AOV IOL measured 0.033 µm and 0.041 µm, respectively, for total ocular spherical aberration postoperatively. Eyes implanted with the Tecnis IOL measured 0.024±0.058 µm for postoperative total ocular spherical aberration, and the SN60WF measured 0.01±0.35 µm. No statistically significant differences were found in total ocular spherical aberration between the two groups (P=.32); because of the small sample size, comparisons were not made with the L161AOV IOL.

When the predicted total ocular spherical aberration was compared to the measured postoperative total ocular spherical aberration, the mean absolute error was 0.025±0.020 µm. Subgroup analysis, assuming equal variance, demonstrated no statistical significance between the mean absolute errors of the Tecnis and SN60WF eyes (P=.76). Additionally, measurements of corneal spherical aberration postoperatively were compared to preoperative values, which revealed no statistical difference (P=.48), irrespective of lens selection. All but three eyes achieved a spherical aberration value within 0.1 µm of the intended zero. Each of the three eyes measured >0.37 µm for preoperative corneal spherical aberration and all eyes, regardless of preoperative measurements, were within 0.15 µm of zero (Fig 2).

DISCUSSION

Precise postoperative outcomes are no longer determined by spherocylindrical refraction outcomes alone. The appreciation of higher order aberrations and their effect on visual performance is well documented.6-11 Combination of aberrations from both the anterior cornea and the internal optics is a delicate process, and aspheric IOLs are designed to mimic the refractive properties of the youthful prolate lens by compensating for the natural prolate surface of the cornea.
This study was intended to determine the capability of managing spherical aberration by coupling preoperative corneal spherical aberration with the appropriate aspheric IOL to achieve a reproducible reduction in total ocular spherical aberration. In the present study, when measured by the OPD-Scan, the average total ocular spherical aberration following corneal spherical aberration-guided cataract surgery is 0.019±0.051 µm.

To adequately investigate the control of postoperative ocular spherical aberration, precise preoperative corneal spherical aberration measurements are required. It is important to remember that the refractive surface that provides the majority of the refractive power of the eye is the anterior cornea surface. Unfortunately, a correlation between corneal radius and keratometry and spherical aberration and Q-value has demonstrated a poor correlation. A significant repeatability of corneal higher order aberration measurement with the Placido-disk–based videokeratoscope has been reported previously, as well as the effect small-incision cataract surgery has on corneal spherical aberration. Tong et al when calculated with the Humphrey Atlas topographer (Carl Zeiss Meditec) and customized MatLab ray-tracing program (The MathWorks Inc, Natick, Mass), found a 3.0-mm clear corneal incision merely reduced corneal spherical aberration by an average 0.016 µm. In the current study, a similar degree of consistency was found with pre- and postoperative corneal spherical aberration (preoperative corneal spherical aberration 0.260±0.084 µm/postoperative corneal spherical aberration 0.247±0.089 µm [P=.48]).

Postoperative ocular spherical aberration has been reported previously in eyes implanted with aspheric IOLs and compared to eyes implanted with spheric IOLs. Awwad et al found that when measured at a 6.0-mm pupil with the LADARWave aberrometer (Alcon Laboratories Inc), 15 eyes implanted with an AcrySof SN60WF IOL significantly reduced ocular spherical aberration 0.09±0.04 µm when compared to 13 eyes implanted with an AcrySof SN60AT IOL (Z[4,0] = 0.43±0.12 µm) (P<.0001). Caporossi et al and Kasper et al both measured total ocular spherical aberration with the Zywave aberrometer (Bausch & Lomb). The former study calculated postoperative spherical aberration as 0.05±0.06 µm at a 5.0-mm pupil for the Tecnis Z9000, 0.11±0.1 µm for the AcrySof SN60WF, and 0.19±0.08 µm for the Sofport L161AO, whereas Kasper et al implanted 20 eyes with the Tecnis Z9000 IOL and calculated a mean postoperative ocular spherical aberration of +0.17 µm and a mesopic pupil diameter of 3.84 mm.

The LADARWave and the Zywave are both Hartmann-Shack aberrometers, which are objective, parallel, double-pass methods and therefore limited in their spatial resolution by the number and size of the microlens. In addition, neither the LADARWave nor the Zywave are capable of measuring the corneal spherical aberration alone. As a result, in the study by Caporossi et al, the corneal spherical aberration was derived from analysis of the corneal elevation data of the Zernike coefficients using a separate corneal topographer (Eye-Top; Costruttori Strumenti Oftalmici, Florence, Italy). Kasper et al was forced to generate measurements of corneal spherical aberration with the Orbscan IIz (Bausch & Lomb). The use of two instruments, which require a patient change position to calculate the corneal spherical aberration and the ocular spherical aberration has the potential to introduce error, such as cyclotorsion. Unique to the OPD-Scan is the integrated corneal topographer, which enables corneal wavefront and total ocular wavefront data to be generated within 0.2 seconds of each other aided by a built-in eye tracker to ensure direct correlation and minimize the chance for movement.

Furthermore, the aforementioned Hartmann-Shack aberrometers calculate ocular spherical aberration relative to the line of sight, or the axis joining the pupillary center to the fovea, whereas Placido-based topographers use the vertex normal as the derivative for corneal spherical aberration. Salmon et al reported on subtle underestimates of fourth order aberrations owing to the lack of a common axis. In the current study, the OPD-Scan calculates both total and corneal aberrations with regard to the vertex normal, without the need for realignment, thereby avoiding the ambiguity of locating the pupil center that is known to change with pupil size. In fact, the power of the study is best appreciated when we compare the postoperative total ocular spherical aberration to the predicted total ocular spherical aberration. For all eyes in our study, the mean absolute error is 0.025±0.020 µm. Previously, Packer et al using the iTrace (Tracey Technologies, Houston, Tex) to calculate the corneal spherical aberration, and then measuring postoperative ocular spherical aberration with the WASCA aberrometer (AMO Wavefront Sciences LLC, Albuquerque, NM) achieved a similar predictive value when selecting an IOL based on corneal spherical aberration. Both aberrometers in their study measured ocular wavefront slope from the line of sight. Despite the discrepancy in vertex normal and line of sight, previously published data have demonstrated reproducible correlation between total aberration measured by the iTrace and OPD-Scan. Furthermore, should alignment be a significant concern, the anticipated effect would be elevated coma, which was not evaluated in either study and remains a source for future research.
Aside from line of sight misalignment, when interpreting these data we must also remain cognizant of the aspheric IOL’s sensitivity to positioning and acknowledge the possible contribution that tilt, decentration, and defocus may have in neutralizing total ocular higher order aberrations, as well as spherical aberration. Although a more thorough optical analysis of IOL centration represents a deficiency in the study, it was presumed that the presence of a continuous curvilinear capsulorhexis with 360° anterior capsular contact minimized any effective of tilt or decentration.

As a feasibility study, we were concerned about the potential for over- and under-estimation of both the measurement and calculation of lower and higher order aberrations. He et al10 suggested that there are some compensatory factors between both eyes that in part are responsible for the aberrations in the cornea and the whole eye. Therefore, in the design of this study, only one eye of each patient was included to eliminate the effective exaggeration of statistical tests as aberrations in right and left eyes exhibit some degree of correlation.14,31

Consistent with reports suggesting super vision is found with greater prevalence in individuals with slightly positive ocular spherical aberration,10,11 Beiko12 found improved contrast sensitivity under photopic and mesopic conditions with a targeted residual ocular Z(4,0) of +0.10 µm. This differs from the study by Piers et al,13 which demonstrated in-focus contrast performance peaks with 0.0 µm of Z(4,0) using an adaptive optics vision simulator with five eyes of five patients. Further experimentation with adaptive optics by Wang et al12 showed that for a 6.0-mm pupil and zero defocus, the optimal ocular Z(4,0) was slightly negative (−0.05 µm), shifting toward +0.20 µm with myopia of −0.50 D, and back toward −0.30 µm with hyperopia of +0.50 D. Image quality appears to be maximized through an inverse relationship between defocus and spherical aberration, although this remains a topic for further research.

Considering the variability in the literature combined with the propensity to err on the side of low levels of myopia when calculating lens power, it was our decision to aim for near total elimination of spherical aberration. Although −0.11 ± 0.33 D is the measured postoperative mean spherical equivalent refraction for all eyes, −0.01 ± 0.35 D, −0.12 ± 0.35 D, and −0.31 D are the postoperative mean spherical equivalent refraction for the Tecnis, SN60WF, and L161AOV IOLs, respectively. In turn, postoperative total ocular spherical aberration for all eyes measured 0.02 ± 0.051 µm and 0.024 ± 0.58 µm for the Tecnis group, 0.01 ± 0.35 µm for the SN60WF group, and 0.04 µm for the two eyes implanted with the L161AOV. This relationship between lower order and higher order aberrations is important to acknowledge as it appears to correlate most strongly with visual performance.

Although limited in scope, this study demonstrates the feasibility of analyzing preoperative corneal spherical aberration and calculating ocular spherical aberration following aspheric IOL selection. Furthermore, dynamic skiascopy appears to be a reproducible method for calculating higher order aberration, specifically spherical aberration in the pseudophakic eye. Further clinical study is desirable to address the effective quality of vision.

REFERENCES
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