LABORATORY SCIENCE

Astigmatism induced by intraocular lens tilt evaluated via ray tracing

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Purpose: To evaluate astigmatism induced by aspheric and toric intraocular lens (IOL) tilt using a ray-tracing model.

Setting: Cullen Eye Institute, Baylor College of Medicine, Houston, Texas, USA.

Design: Experimental study.

Methods: Ray-tracing eye models with aspheric IOLs (16.0 diopters [D], 22.0 D, and 28.0 D) and toric IOLs (16.0 D, 22.0 D, and 28.0 D each with toricities of 1.50 D, 3.75 D, and 6.00 D) were used. The IOLs were tilted from 1 to 10 degrees horizontally around a 90-degree vertical meridian. Toric IOLs were aligned at 90 degrees and 180 degrees to correct with-the-rule (WTR) and against-the-rule (ATR) corneal astigmatism, respectively. Astigmatism at the corneal plane induced by IOL tilt was calculated.

Results: Induced astigmatism increased with increasing IOL tilt and power. Horizontal tilt around a vertical meridian induced ATR astigmatism. For 5 degrees of tilt, induced astigmatism was 0.08 D, 0.11 D, and 0.14 D for 16.0 D, 22.0 D, and 28.0 D aspheric IOLs, respectively. Ten degrees of IOL tilt produced 0.33 D, 0.44 D, and 0.56 D of induced astigmatism for 16.0 D, 22.0 D, and 28.0 D aspheric IOLs, respectively. Tilting toric IOLs aligned at 90 degrees around a vertical meridian increased the magnitude of induced ATR astigmatism. Tilting toric IOLs aligned at 180 degrees decreased the magnitude of induced WTR astigmatism.

Conclusions: Tilting aspheric IOLs horizontally around a vertical meridian induced ATR astigmatism. Tilting toric IOLs aligned at 90 degrees increased ATR astigmatism, resulting in overcorrection. Tilting toric IOLs aligned at 180 degrees decreased WTR astigmatism, producing undercorrection.

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Intraocular lens (IOL) tilt has the potential to induce astigmatism. Until now, IOL tilt could not be measured routinely in the clinical setting because a separate device, such as the ultrasound biomicroscope, Purkinje reflection device, Scheimpflug camera system, or anterior segment optical coherence tomography (OCT), was needed.[1–4] Recently, swept-source OCT (SS-OCT) biometers were introduced; these include the IOLMaster 700 (Carl Zeiss Meditec AG), Argos (Movu, Inc.), and OA-2000 (Tomey Corp.). Recent studies using the IOLMaster 700 SS-OCT[A,5] reported that this device can measure crystalline lens tilt, and preoperative phakic lens tilt can be used to predict postoperative IOL tilt. This makes it possible to obtain crystalline lens or IOL tilt information during optical biometry and perhaps factor its effect into the selection of IOL toricity.

The impact of tilted or decentered IOLs on retinal image quality has been investigated using an optical bench, adaptive optics, and in clinical patients.[6–8] However, data on the effect of IOL tilt on induced astigmatism are scarce. The purpose of this study was to evaluate the astigmatism induced by aspheric and toric IOL tilt in a theoretical model constructed using optical design software.

MATERIALS AND METHODS

Eye Model

Opticstudio (Zemax, LLC) generates ray tracing models of optical systems from user-designed specifications. With this software, theoretical eye models were constructed using the parameters outlined below.

Corneal Data The cornea was modeled as 2 aspheric surfaces with a central thickness of 0.550 mm. Detailed parameters are listed in Table 1 and are the same as those used in the study by Holladay and Simpson.[9]

Pupil Plane The pupillary aperture was set at 6.00 mm and was placed 4.05 mm behind the anterior corneal surface.

Intraocular Lens Data The anterior IOL surface was placed 0.50 mm behind the pupil plane or 4.55 mm posterior to the

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anterior corneal surface. Aspheric IOLs and toric IOLs were included in the eye models.

For aspheric IOLs, the specific optical parameters for the Acrysof IQ monofocal IOL (SN60WF) were provided by the manufacturer, Alcon Laboratories, Inc. The parameters included the anterior and posterior curvatures, asphericity, and thickness. Eye models with powers of 16.0 diopters (D), 22.0 D, and 28.0 D were constructed.

For toric IOLs, specific optical parameters were not available for the Acrysof IQ. Thus, general optical parameters for the SN60WF, including the lens asphericity conic constant and lens thickness, were used for toric IOL construction. To create a toric IOL with a specific lens power, the anterior radius of curvature of a SN60WF IOL with the same refractive power was used. The radii of curvature for the steep and flat meridians of the posterior surface were then determined using OpticStudio optical design software to produce the desired overall IOL power. For example, to create a 22.0 D lens with a cylinder power of 6.0 D, the radius of curvature on the anterior surface was the same as the radius of curvature on the anterior surface for a 22.0 D aspheric IOL and radii of curvature to produce equivalent power of 19.0 D and 25.0 D were determined and used for the flat meridian and steep meridian on the back surface. Eye models were constructed using 16.0 D, 22.0 D, and 28.0 D toric IOLs with cylinder powers of 1.50 D (SN6AT3), 3.75 D (SN6AT6), and 6.00 D (SN6AT9).

Intraocular Lens Tilt

Previous studies[A,4] have reported that IOLs were tilted greatest in a nasal direction. In the model used, aspheric IOLs and toric IOLs were tilted horizontally around a vertical meridian with the nasal border tilted anteriorly and the temporal border tilted posteriorly in 1-degree steps up to 10 degrees.

For the toric IOLs, horizontal lens tilt was performed with the IOLs aligned at 90 degrees (as if correcting with-the-rule [WTR] corneal astigmatism) and at 180 degrees (as if correcting against-the-rule [ATR] corneal astigmatism).

Data Analysis

For each eye model and IOL power, the ray-tracing software was used to optimize the vitreous cavity length before the IOL was titled. Wavefront aberrations at the corneal plane up to the 7th order were calculated for a 6.0 mm pupil and IOL tilt from 0 to 10 degrees. Second-order astigmatism data without and with IOL tilt were evaluated. Because the IOL was tilted horizontally, only the astigmatism term Z(2,2) was relevant in this study. For easy comprehension, Zernike coefficient values of the 2nd-order astigmatism Z(2,2) (C_2^2) in micrometers were converted to diopters (D) using the following equation:

$$C = 4\sqrt{6}\,C_2^2/R^2$$

Table 1. Nominal values used in the eye model.

Parameter	Value
Corneal anterior surface radius (mm)	7.76
Corneal anterior surface Q value	−0.26
Corneal index of refraction @555 nm	1.376
Corneal thickness (mm)	0.55
Corneal posterior surface radius (mm)	6.36
Corneal posterior surface Q value	−0.24
Pupil plane behind anterior corneal surface (mm)	4.05
IOL anterior surface plane behind anterior corneal surface (mm)	4.55

IOL = intraocular lens; Q value = asphericity

where C is the dioptric power of the cylinder and R is the radius of the pupil in mm. This equation is a modification of the original conversion equation $C = -4\sqrt{6}\,C_2^2/R^2$ described by Applegate et al.[10] In this study, the equivalent dioptric power of C_2^2 in micrometers, not the traditional cylinder correction format, was calculated. The 2nd-order astigmatism induced by IOL tilt at corneal plane was calculated.

RESULTS

Aspheric Intraocular Lens Tilt

Figure 1 shows the aspheric IOL tilt-induced ATR astigmatism. Table 2 shows the induced 2nd-order astigmatism by degree of tilt.

The astigmatism induced by IOL tilt increased as both IOL tilt and power were increased.

Toric Intraocular Lens Tilt

Toric IOL tilt induced astigmatism that was dependent on IOL alignment and power (Figure 2 and Table 2). When the toric IOLs were aligned at 90 degrees, IOL tilt increased the ATR astigmatic effect at the corneal plane. The induced ATR astigmatism also increased as tilt increased. When the toric IOLs were aligned at 180 degrees, IOL tilt decreased the WTR astigmatic effect at the corneal plane. The deduction in WTR astigmatism increased as tilt increased and decreased as toricity increased.

DISCUSSION

In a previous study using the IOLMaster 700 SS-OCT biometer to examine postoperative IOL position, Hirnschall et al.[5] found IOL tilt was greatest in a horizontal direction (around a vertical meridian) with the nasal border displaced anteriorly and the temporal border displaced posteriorly at an average magnitude of 6.2 degrees. Tilt direction and magnitude were similar in right eyes and left eyes. In a comparable study at our institution,[A] we found similar tilt directions and magnitudes, with a mean IOL tilt of 4.9 degrees (range 2 to 10 degrees).

In this study, which used OpticStudio ray-tracing software, we evaluated the astigmatism induced by aspheric and toric IOL tilts ranging from 0 to 10 degrees. We also investigated the effect of IOL power, IOL toricity, and toric

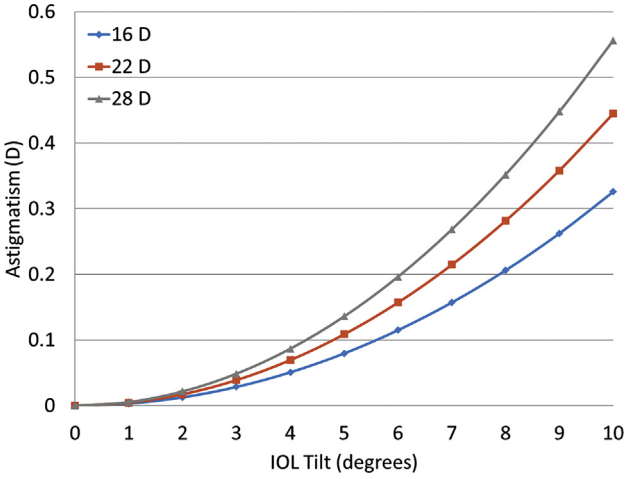

Figure 1. Tilt-induced ATR astigmatism (D) in eyes with aspheric IOLs (ATR = against-the-rule; IOL = intraocular lens).