

Optical performance of toric intraocular lenses in the presence of decentration

Bin Zhang, Jin-Xue Ma, Dan-Yan Liu, Ying-Hua Du, Cong-Rong Guo, Yue-Xian Cui

Department of Ophthalmology, the Second Hospital of Hebei Medical University, Shijiazhuang 050000, Hebei Province, China

Correspondence to: Jin-Xue Ma. Department of Ophthalmology, the Second Hospital of Hebei Medical University, No.215 Hepingxi Road, Shijiazhuang 050000, Hebei Province, China. zbdoccn@126.com

Received: 2014-05-04

Accepted: 2014-11-03

Abstract

• **AIM:** To evaluate the optical performance of toric intraocular lenses (IOLs) after decentration and with different pupil diameters, but with the IOL astigmatic axis aligned.

• **METHODS:** Optical performances of toric T5 and SN60AT spherical IOLs after decentration were tested on a theoretical pseudophakic model eye based on the Hwey-Lan Liou schematic eye using the Zemax ray-tracing program. Changes in optical performance were analyzed in model eyes with 3-mm, 4-mm, and 5-mm pupil diameters and decentered from 0.25 mm to 0.75 mm with an interval of 5° at the meridian direction from 0° to 90°. The ratio of the modulation transfer function (MTF) between a decentered and a centered IOL ($MTF_{Decentration}/MTF_{Centration}$) was calculated to analyze the decrease in optical performance.

• **RESULTS:** Optical performance of the toric IOL remained unchanged when IOLs were decentered in any meridian direction. The MTFs of the two IOLs decreased, whereas optical performance remained equivalent after decentration. The $MTF_{Decentration}/MTF_{Centration}$ ratios of the IOLs at a decentration from 0.25 mm to 0.75 mm were comparable in the toric and SN60AT IOLs. After decentration, MTF decreased further, with the MTF of the toric IOL being slightly lower than that of the SN60AT IOL. Imaging qualities of the two IOLs decreased when the pupil diameter and the degree of decentration increased, but the decrease was similar in the toric and spherical IOLs.

• **CONCLUSION:** Toric IOLs were comparable to spherical IOLs in terms of tolerance to decentration at the correct axial position.

• **KEYWORDS:** lens; artificial; astigmatism; cornea; decentration; model

DOI:10.3980/j.issn.2222-3959.2015.04.16

Zhang B, Ma JX, Liu DY, Du YH, Guo CR, Cui YX. Optical performance of toric intraocular lenses in the presence of decentration. *Int J Ophthalmol* 2015;8(4):730-735

INTRODUCTION

Corneal astigmatism is a common form of ametropia, and approximately 15% -50% of cataract patients have concomitant corneal astigmatism of varying degrees^[1-3]. The implantation of toric intraocular lenses (IOLs) during cataract surgeries has been proven effective for correcting corneal astigmatism^[4-7]. It has been reported that toric IOLs have satisfactory rotational stability^[7-9], which has been considered to be advantageous for patients. The toric IOL consists of a spherical anterior surface and a toric posterior surface. The two crossed vertical meridians at the posterior surface have different curvature radii, and the refractive cylinder obtained from the diopter difference is used to correct the corneal astigmatism.

Certain IOLs are manufactured with specific surface characteristics, such as aspheric IOLs with a -0.27 μm spherical aberration (SA). These characteristics have been associated with excellent imaging quality when the IOL was implanted and maintained in the correct position and the corneal SA could be effectively offset^[10-14]. However, optical performance has been reported to be significantly compromised when the decentration is more than 0.5 mm^[13-15]. More specifically, a study of the tilt and decentration of these IOLs demonstrated an optic quality decrease correlated with coma aberration^[13].

The anterior surface of the AcrySof toric IOL is spherical, and the posterior surface is toric. The spherical diopter is contributed by both the anterior and posterior surfaces, and the cylinder diopter is contributed solely by the posterior surface, with the axial position marked. The cylinder diopter and axis position of the implanted toric IOL need to be accurate to neutralize corneal astigmatism^[4,5,16,17]. Most reports pay close attention to off-axis rotation and rotational stability of the toric IOL. The rotational stability of the toric IOL within the eye has been reported to be satisfactory, with an average postoperative rotation between 2.7° and 4.1°^[8,18]. For toric IOL rotation, the cornea and toric IOL can be regarded as two obliquely crossed cylinders. The combined effect of the obliquely crossed cylinders creates a new cylinder power and axis, which differ based on the intended

Table 1 Optical characteristics of the Hwey-Lan Liou schematic eye

Surface	Radius (mm)	Asphericity (Q)	Thickness (mm)	<i>n</i>
Anterior corneal	7.77	-0.18	0.50	1.376
Posterior corneal	6.40	-0.60	3.16	1.336
Anterior lens	12.40	-0.94	1.59	1.368-1.407
-	∞	-	2.43	1.407-1.368
Posterior lens	-8.10	+0.96	16.7	1.336
Retina	-12.3	0	-	-

target [18,19]. The astigmatism correction effect was reduced by 3.3% for each 1° of rotation deviation [20,21]. Therefore, concerns have been raised regarding the rotation stability of the toric IOL. Felipe *et al* [22] reported that the modulation transfer function (MTF) on the high and low power axes of the toric IOL decays with rotation and tilt, with greater decrement occurring in rotation from 0° to 5° in model eyes. However, the artificial eye model used in the study included an artificial cornea without astigmatism to simulate the conditions of the eye.

Corneal astigmatism is characterized by a gradual refractive change in diopters (D) from a flat to a steep meridian, which is similar to the toric IOL. Therefore, the refractive power is different on a 0° to 90° meridian in corneal astigmatism. However, the influence of the different direction of meridian decentration on the optical performance of the toric IOL and its tolerance to decentration have yet to be clearly defined. As such, we are interested in how much optical quality is lost when the toric IOL optic center is off-axis in corneal astigmatism.

MTF has been demonstrated to be a highly effective parameter to evaluate IOL optical performance [23,24], and is used to represent image quality. In the current study, we created the concept of relative decreased optical quality by calculating $MTF_{Decentration}/MTF_{Centration}$ ratios derived from MTF to evaluate the tolerance to toric lens decentration. The influence of 0.25 mm, 0.5 mm, and 0.75 mm decentration in different meridian directions was studied with regard to the optical performance of the AcrySof Toric SN60T5 and SN60AT spherical IOLs in the setting of the Hwey-Lan Liou eye model with different pupil diameters (3, 4, and 5 mm).

MATERIALS AND METHODS

Pseudophakic Model Eye The imaging qualities of the AcrySof Toric SN60T5 IOL (Alcon Laboratories Inc., Ft Worth, TX, USA) and the SN60AT spherical IOL (Alcon Laboratories Inc., Ft Worth, TX, USA) were tested on a theoretical pseudophakic model eye using the Zemax (Focus Software, Tucson, AZ, USA) ray-tracing program. As previously mentioned, the Hwey-Lan Liou eye model was used, and IOLs were evaluated instead of natural human lenses. The specifications of the Hwey-Lan Liou eye model are shown in Table 1 [25]. The power of both IOLs was 22.0 D. The cylinder D of the toric T5 IOL was 3.0 D, which has been used to correct corneal astigmatisms of 2.06 D. The optical characteristics and technical specifications of the two

Table 2 Optical characteristics of the spherical and AcrySof Toric IOLs

Parameters	SN60AT	Toric T5
Manufacturer	Alcon	Alcon
Power (D)	+22.0	+22.0
Optic material	Acrylic	Acrylic
Refractive index	1.55	1.55
Lens shape	Equal-convex	Biconvex toric
Anterior surface	Sphere	Sphere
Radius (mm)	19.22	19.607
Central thickness (mm)	0.6	0.699
Posterior surface	Sphere	Toric
Radius (mm)	-19.22	Steep -17.836 Flat -23.782
Optic size (mm)	6.0	6.0
Overall length (mm)	13.0	12.0
A constant	118.4	119.0
Hepatic material	Acrylic	Acrylic
Cylinder power at IOL plane		3.00 D
Cylinder power at corneal plane		2.06 D
Abbe number	37	37

IOLs are shown in Table 2 [26-28].

The optical performance of each IOL was evaluated in the Hwey-Lan Liou schematic eye, with a distance of 4.5 mm between the anterior surface of the IOL and the anterior surface of the cornea [13,29,30]. The flat and steep axes of the toric T5 IOL were aligned with the x- and y-axes, respectively. The vitreous cavity length was modified to achieve y-axis focus on the retina. Then, the curvature of the x-axis was adjusted by adding an ideal thin lens in front of cornea in order to achieve concurrent x-axis focus on the retina. An astigmatism model which could be completely corrected by the toric IOL was established (Figure 1). The optical performance was optimized by adjusting the curvature of the x- direction and the distance between the retina and posterior surface of the IOLs after one ideal thin lens was inserted in front of the cornea of the toric IOL model eye with a pupil diameter of 3 mm. The distance between the posterior surface of the IOLs and the retina was optimized in the SN60AT IOL model eye to focus the light on the retina.

Simulating the Condition of Decentration and Plotting the Modulation Transfer Function The ideal thin lens with the corresponding cylinder D (2.17 D for T5) was obtained. The distance to the retina was not optimized any further following changes in pupil diameter and decentration.

Table 3 The modulation transfer function of intraocular lens decentration at spatial frequencies of 40 cycles/mm with 3, 4, and 5 mm pupil diameters

Decentration	SN60AT			Toric T5		
	3 mm	4 mm	5 mm	3 mm	4 mm	5 mm
0	0.791504	0.427848	0.294706	0.790613	0.401795	0.294187
0.25 mm	0.755886	0.40346	0.269066	0.726577	0.363624	0.238585
0.5 mm	0.711562	0.374794	0.25492	0.675183	0.33148	0.238585
0.75 mm	0.661697	0.526572	0.235175	0.623793	0.315	0.2277

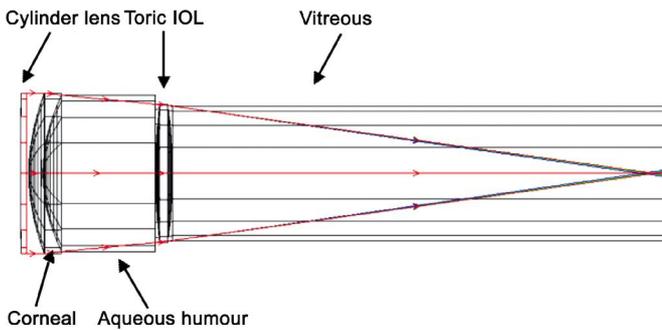


Figure 1 The theoretical pseudophakic model eye in Zemax.

The simulation of IOL decentration in the model eye was measured along 19 meridians from 0° to 90° at 5° intervals with decentrations of 0.25, 0.5, and 0.75 mm, respectively. The cornea and pupil were always centered on the optical axis of the model eye.

The MTF was computed using Zemax software for each simulation, and an array of 512 × 512 rays was traced. MTFs were plotted for each simulation at spatial frequencies of 20 cycles/mm and 40 cycles/mm, respectively.

Calculating the Modulation Transfer Function Ratio

The ratio of the MTF between a perfectly centered IOL and a decentered IOL ($MTF_{Decentration}/MTF_{Centration}$) was calculated to analyze the decrease in optical performance using pupil diameters of 3, 4, and 5 mm, respectively.

RESULTS

Modulation Transfer Function of Intraocular Lens Decentration As presented in Table 3, the MTF of the toric T5 IOL was slightly lower than that of the SN60AT IOL at all decentration conditions with different pupil diameters.

Under the conditions of a 3 mm pupil diameter, the MTF was decreased in both IOLs when they were decentered to 0.5 mm along the meridian from 0° to 90°, and the optical performance was comparable in two IOLs. The MTF values were further decreased when decentering to 0.75 mm at the spatial frequency of 40 cycles/mm, and the imaging quality of the toric and SN60AT IOLs remained very comparable (Figure 2A).

Under the conditions of a 4 mm or 5 mm pupil diameter, the MTF values of the two IOLs were significantly decreased at the two spatial frequencies, and were significantly lower than MTF values obtained at the pupil diameter of 3 mm. The MTF values were further decreased when decentering to

0.5 mm (Figure 2B) and 0.75 mm (Figure 2C). The MTF values for the toric IOL were slightly lower than those for the spherical IOL. The optical performance of the non-rotating symmetrical toric IOL in the settings of 0.5 mm and 0.75 mm decentration was comparable to that of the SN60AT IOL. The imaging quality of the toric IOL was not altered significantly when decentered in any direction.

The $MTF_{Decentration}/MTF_{Centration}$ Ratios The $MTF_{Decentration}/MTF_{Centration}$ ratios of the IOLs in model eyes with 3, 4, and 5 mm pupil diameters and at decentrations of 0.25, 0.5, and 0.75 mm, showed comparable optical performance for both IOLs. When the pupil diameter was 5 mm and the decentration was 0.5 mm at a spatial frequency of 20 cycles/mm, the $MTF_{Decentration}/MTF_{Centration}$ ratios of the SN60AT and T5 IOLs were 0.893 and 0.846, respectively. With 0.75 mm decentration, the ratios were 0.814 and 0.799, respectively. The maximum difference in the optical performance between the toric T5 and SN60AT IOLs was only 4.7% under the condition of a 5 mm pupil diameter and a spatial frequency of 20 cycles/mm (Figure 3).

DISCUSSION

Our results demonstrated that the optic quality of the toric IOL with an accurate axis was not affected by the decentration direction, and that the tolerance to decentration was similar to the spherical IOL. The refractive power of symmetric spherical or aspherical corneas remained equal at all meridians, and the decentration of IOLs in each direction, in the case of pupil centration, had the same effect on imaging quality [31,32]. However, corneal astigmatism is characterized by a gradual refractive alteration in the Ds from a flat to a steep meridian, which is similar to the toric IOL. Many conditions, such as a large lens capsule, asymmetry of the capsular bag coverage, capsular phimosis or fibrosis, and capsular radial tears, may also result in the decentration of IOLs [33-35].

Several studies have examined the effects of decentration on spherical and non-spherical IOLs and its influence on imaging quality. Findings from these studies suggest that the decentration and tilt in the implanted IOLs formed regardless of whether spherical, non-spherical, or toric IOLs were used [33,34,36,37].

In the current study, changes in the MTF of the toric IOL at spatial frequencies of 20 cycles/mm and 40 cycles/mm were

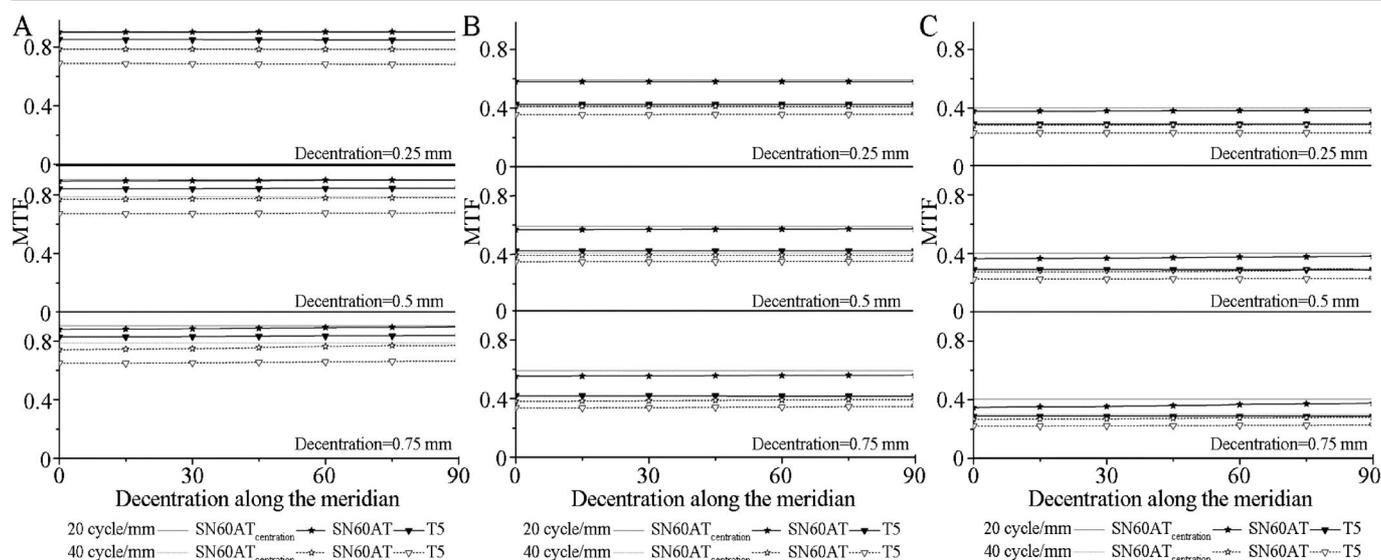


Figure 2 The MTF curves of the pseudophakic model eye with pupil diameters of 3, 4, and 5 mm. The MTF was decreased in both IOLs with decentrations from 0.25 mm to 0.75 mm A: The MTF curves of the model eye with a 3 mm pupil. Although the MTF values for the toric IOL were slightly lower than those for the spherical IOL, the MTF of the toric IOL was not affected when decentration was along meridians in different directions; B: The MTF curves with a pupil diameter of 4 mm. The imaging quality of the toric IOL was not altered significantly when decentered in any direction; C: The MTF curves with a pupil diameter of 5 mm. The MTF values of the two IOLs were significantly lower than MTF values obtained at the 3 mm pupil diameter. The imaging quality of the toric IOL was not altered significantly when decentered in any direction.

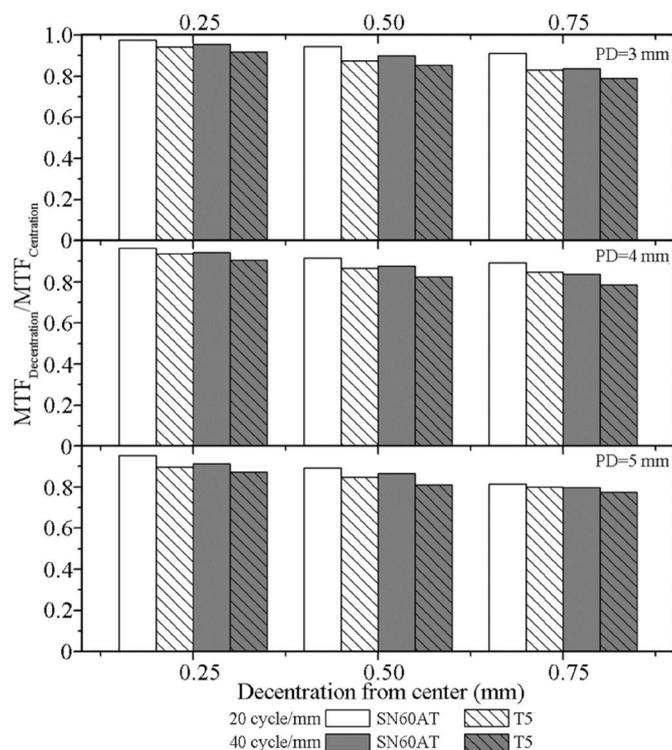


Figure 3 The ratios of $MTF_{Decentration}/MTF_{Centration}$ in the pseudophakic model eyes with 3, 4, and 5 mm pupil diameters, with decentrations from 0.25 mm and 0.75 mm at spatial frequencies of 20 cycles/mm and 40 cycles/mm, respectively The ratios were decreased in both IOLs, but remained comparable to each other.

studied. Contrast sensitivity is usually measured in spatial frequencies of 1.5, 3, 6, and 12 cycles per degree (cpd), as Nio *et al* [38] believed that the contrast sensitivity of normal

human eyes reaches its peak at 4-8 cpd. For visual acuity measurements, higher spatial frequencies are considered to be more important when visual acuity exceeds 20/40 [39]. The 20 cycles/mm and 40 cycles/mm spatial frequencies used in Zemax are equal to 6 and 12 cpd of contrast sensitivity after unit conversion, respectively.

The MTF of the toric IOL was lower than that of the spherical IOL, both with centration and decentration. The model eye, after the astigmatism was completely corrected, is similar to the SN60AT IOL in terms of spherical characterization. When centered, the toric IOL showed a slightly lower MTF than the AN60AT IOL. Felipe *et al* [22] reported that the toric IOL presented a similar MTF as compared to the spherical IOL, and exhibited good optical quality on the high and low power axes, although they were not assessed at the same powers. However, the study used an eye model that included an artificial cornea without astigmatism. With increasing degrees of decentration, spherical IOLs and toric IOLs showed lower MTFs, with the toric IOL showing a lower MTF than the SN60AT IOL. Although the astigmatism D of the cornea could be adjusted by a toric IOL, the vertical and horizontal lengths of the image were not equal. The magnification of low and high power radials differed by 1%-3%, and this magnification difference affected the optic quality, as manifested by tensile deformation of the image [40]. In the current study, we observed the changes of wavefront aberration in the course of decentration, and found that the coma of the toric IOL increased. Increasing of the coma may have contributed to

the lower optical quality associated with the toric IOL as compared to the SN60AT IOL.

The IOL decentration was simulated for 0.25 mm, 0.5 mm, and 0.75 mm in the meridian direction from 0° to 90°. Although the MTF of the toric IOL was lower than that of the spherical IOL, the asymmetry of the cornea and posterior surface of the toric IOL had no effect on the decentration of the toric IOL towards different directions, and the optical performance remained the same at the same decentration. Although the optic center of the toric IOL decentered from the optic axis, the axis astigmatism of the toric IOL maintained acuity, and the corneal astigmatism was neutralized. In order to determine whether the optical performance was influenced differently by the decentration between the two IOLs, the ratio of $MTF_{Decentration}/MTF_{Centration}$ was compared, and was found to be decreased markedly at 0.75 mm decentration as compared to 0.5 mm decentration. This suggests that the degree of decentration was negatively correlated with optical performance^[32], although the values of the $MTF_{Decentration}/MTF_{Centration}$ ratios were quite comparable for the two IOLs. Therefore, we can conclude that the tolerance to decentration was similar in the spherical and toric IOLs.

When the model eye had an accurate axis of the toric IOL and astigmatism was completely corrected, the optical performance of the toric IOL was slightly lower than that of the spherical IOL. The decrease in optical performance due to decentration was similar in both the toric and spherical IOLs with different pupil diameters. Toric IOLs were comparable to spherical IOLs in terms of tolerance to decentration when the axis was aligned, and the decentration in any direction of the meridian had a similar influence on optical performance.

ACKNOWLEDGEMENTS

Conflicts of Interest: Zhang B, None; Ma JX, None; Liu DY, None; Du YH, None; Guo CR, None; Cui YX, None.

REFERENCES

- 1 Hoffer KJ. Biometry of 7,500 cataractous eyes. *Am J Ophthalmol* 1980; 90(3):360–368
- 2 Khan MI, Muhtaseb M. Prevalence of corneal astigmatism in patients having routine cataract surgery at a teaching hospital in the United Kingdom. *J Cataract Refract Surg* 2011; 37(10):1751–1755
- 3 De Bernardo M, Zeppa L, Cennamo M, Iaccarino S, Zeppa L, Rosa N. Prevalence of corneal astigmatism before cataract surgery in Caucasian patients. *Eur J Ophthalmol* 2014; 24(4):494–500
- 4 Ernest P, Potvin R. Effects of preoperative corneal astigmatism orientation on results with a low-cylinder-power toric intraocular lens. *J Cataract Refract Surg* 2011; 37(4):727–732
- 5 Hasegawa Y, Okamoto F, Nakano S, Hiraoka T, Oshika T. Effect of preoperative corneal astigmatism orientation on results with a toric intraocular lens. *J Cataract Refract Surg* 2013; 39(12):1846–1851
- 6 Iovieno A, Yeung SN, Lichtinger A, Alangh M, Slomovic AR, Rootman DS. Cataract surgery with toric intraocular lens for correction of high corneal astigmatism. *Can J Ophthalmol* 2013; 48(4):246–250
- 7 Carey PJ, Leccisotti A, McGilligan VE, Goodall EA, Moore CB. Assessment of toric intraocular lens alignment by a refractive power/corneal analyzer system and slitlamp observation. *J Cataract Refract Surg* 2010; 36(2):222–229
- 8 Sanders DR, Sarver EJ, Cooke DL. Accuracy and precision of a new system for measuring toric intraocular lens axis rotation. *J Cataract Refract Surg* 2013; 39(8):1190–1195
- 9 Hirschschall N, Maedel S, Weber M, Findl O. Rotational stability of a single-piece toric acrylic intraocular lens: a pilot study. *Am J Ophthalmol* 2014; 157(2):405–411
- 10 Taberner J, Piers P, Benito A, Redondo M, Artal P. Predicting the optical performance of eyes implanted with IOLs to correct spherical aberration. *Invest Ophthalmol Vis Sci* 2006; 47(10):4651–4658
- 11 Piers PA, Fernandez EJ, Manzanera S, Norrby S, Artal P. Adaptive optics simulation of intraocular lenses with modified spherical aberration. *Invest Ophthalmol Vis Sci* 2004; 45(12):4601–4610
- 12 Holladay JT, Piers PA, Koranyi G, van der Mooren M, Norrby NE. A new intraocular lens design to reduce spherical aberration of pseudophakic eyes. *J Refract Surg* 2002; 18(6):683–691
- 13 Altmann GE, Nichamin LD, Lane SS, Pepose JS. Optical performance of 3 intraocular lens designs in the presence of decentration. *J Cataract Refract Surg* 2005; 31(3):574–585
- 14 Peh S, Fiala W, Malz A, Stork W. In vitro strehl ratios with spherical, aberration-free, average, and customized spherical aberration-correcting intraocular lenses. *Invest Ophthalmol Vis Sci* 2009; 50(3):1264–1270
- 15 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(10):1841–1851
- 16 Hill W. Expected effects of surgically induced astigmatism on AcrySof toric intraocular lens results. *J Cataract Refract Surg* 2008; 34(3):364–367
- 17 Tsinopoulos IT, Symeonidis C, Tsaousis KT, Tsakpinis D, Ziakas NG, Dimitrakos SA. Intra-operative assessment of toric intra-ocular lens implantation. *Indian J Ophthalmol* 2011; 59(1):60–62
- 18 Tsinopoulos IT, Tsaousis KT, Tsakpinis D, Ziakas NG, Dimitrakos SA. Acrylic toric intraocular lens implantation: a single center experience concerning clinical outcomes and postoperative rotation. *Clin Ophthalmol* 2010; 4:137–142
- 19 Jin H, Limberger IJ, Ehmer A, Guo H, Auffarth GU. Impact of axis misalignment of toric intraocular lenses on refractive outcomes after cataract surgery. *J Cataract Refract Surg* 2010; 36(12):2061–2072
- 20 Shimizu K, Misawa A, Suzuki Y. Toric intraocular lenses: correcting astigmatism while controlling axis shift. *J Cataract Refract Surg* 1994; 20(5):523–526
- 21 Ma JJ, Tseng SS. Simple method for accurate alignment in toric phakic and aphakic intraocular lens implantation. *J Cataract Refract Surg* 2008; 34(10):1631–1636
- 22 Felipe A, Artigas JM, Diez-Ajenjo A, Garcia-Domene C, Peris C. Modulation transfer function of a toric intraocular lens: evaluation of the changes produced by rotation and tilt. *J Refract Surg* 2012; 28(5):335–340
- 23 Madrid-Costa D, Ruiz-Alcocer J, Ferrer-Blasco T, Garcia-Lazaro S, Montes-Mico R. Optical quality differences between three multifocal intraocular lenses: bifocal low add, bifocal moderate add, and trifocal. *J Refract Surg* 2013; 29(11):749–754
- 24 Calatayud A, Remon L, Martos J, Furlan WD, Monsoriu JA. Imaging quality of multifocal intraocular lenses: automated assessment setup. *Ophthalmic Physiol Opt* 2013; 33(4):420–426
- 25 Liou HL, Brennan NA. Anatomically accurate, finite model eye for optical modeling. *J Opt Soc Am A Opt Image Sci Vis* 1997; 14(8):1684–1695

- 26 Barbero S, Marcos S, Montejo J, Dorronsoro C. Design of isoplanatic aspheric monofocal intraocular lenses. *Opt Express* 2011; 19 (7): 6215-6230
- 27 Hong X, Xie J, Van Noy SJ, Stanley D, Karakelle M, Zhang X, Simpson MJ. Alcon Inc. assignee. Intraocular lens. US patent 7350916
- 28 Hong X, Hoffman J, Xie J, Hamlin M. Alcon Inc. assignee. Aspheric toric intraocular lens. US patent 2009/0279048
- 29 Landau IM, Laurell CG. Ultrasound biomicroscopy examination of intraocular lens haptic position after phacoemulsification with continuous curvilinear capsulorhexis and extracapsular cataract extraction with linear capsulotomy. *Acta Ophthalmol Scand* 1999; 77(4):394-396
- 30 Holladay JT, Maverick KJ. Relationship of the actual thick intraocular lens optic to the thin lens equivalent. *Am J Ophthalmol* 1998; 126 (3): 339-347
- 31 Rosales P, De Castro A, Jimenez-Alfaro I, Marcos S. Intraocular lens alignment from purkinje and Scheimpflug imaging. *Clin Exp Optom* 2010; 93(6):400-408
- 32 Eppig T, Scholz K, Loffler A, Messner A, Langenbacher A. Effect of decentration and tilt on the image quality of aspheric intraocular lens designs in a model eye. *J Cataract Refract Surg* 2009;35(6):1091-1100
- 33 van der Linden JW, van der Meulen IJ, Mourits MP, Lapid-Gortzak R. In-the-bag decentration of a hydrophilic radially asymmetric multifocal intraocular lens secondary to capsule contraction. *J Cataract Refract Surg* 2013; 39(4):642-644
- 34 Hayashi K, Harada M, Hayashi H, Nakao F, Hayashi F. Decentration and tilt of polymethyl methacrylate, silicone, and acrylic soft intraocular lenses. *Ophthalmology* 1997; 104(5):793-798
- 35 Walkow T, Anders N, Pham DT, Wollensak J. Causes of severe decentration and subluxation of intraocular lenses. *Graefes Arch Clin Exp Ophthalmol* 1998; 236(1):9-12
- 36 Ale JB. Intraocular lens tilt and decentration: a concern for contemporary IOL designs. *Nepal J Ophthalmol* 2011; 3(1):68-77
- 37 Brandlhuber U, Haritoglou C, Kreutzer TC, Kook D. Reposition of a misaligned Zeiss AT TORBI 709M® intraocular lens 15 months after implantation. *Eur J Ophthalmol* 2014; 24(5):800-802
- 38 Nio YK, Jansonius NM, Fidler V, Geraghty E, Norrby S, Kooijman AC. Norrby S. Age-related changes of defocus-specific contrast sensitivity in healthy subjects. *Ophthalmic Physiol Opt* 2000; 20(4):323-334
- 39 Ginsburg AP. Next generation contrast sensitivity testing. In Rosenthal B, Cole R, eds. *Functional Assessment of Low Vision*. 1st ed. St Louis: Mosby;1996:77-88
- 40 Inoue M, Noda T, Ohnuma K, Bissen-Miyajima H, Hirakata A. Quality of image of grating target placed in model eye and observed through toric intraocular lenses. *Am J Ophthalmol* 2013;155(2):243-252