Multizonal Design Multifocal Intraocular Lens–Induced Astigmatism According to Orientation

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ABSTRACT

PURPOSE: To evaluate the differences in intraocular lens (IOL)–induced astigmatism according to differences in orientation of a multizonal multifocal IOL, the Precizon Presbyopic NVA IOL (Ophtec BV).

METHODS: The clinical study reviewed 80 eyes from 40 patients with cataracts who underwent Precizon Presbyopic IOL implantation. Residual astigmatism, as measured by autorefraction and manifest refraction, was investigated using vector analysis of eyes implanted with vertical (90 ± 30 degrees) and horizontal (180 ± 30 degrees) orientations of the first near segment of the IOL. In the ray-tracing simulation study, pseudophakic eyes with the Precizon Presbyopic IOL were modeled. The modulation transfer function (MTF) of each case was compared with respect to the amount of corneal astigmatism of the model eyes and the orientation of the first near segment.

RESULTS: The mean IOL-induced astigmatism measured by autorefraction was 0.68 ± 0.58 diopters (D) at 1 degree in the vertical orientation of the first near segment (n = 52) and 1.05 ± 0.81 D at 96 degrees in the horizontal orientation (n = 28). However, the mean IOL-induced astigmatism measured by manifest refraction was 0.14 ± 0.44 D at 171 degrees and 0.46 ± 0.40 D at 95 degrees. The MTF analysis showed that the highest MTF values were measured in eyes without corneal astigmatism in both the vertically and horizontally implanted IOLs.

CONCLUSIONS: Autorefraction measurement indicates induction of with-the-rule astigmatism by the Precizon Presbyopic IOL when implanted vertically with respect to the first near segment, and against-the-rule astigmatism when implanted horizontally. However, this astigmatism is clinically insignificant according to manifest refraction and ray-tracing simulation.

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Cataract removal and intraocular lens (IOL) implantation improve vision. In particular, multifocal IOLs improve not only distance vision but also near and intermediate vision, and yield a high level of overall patient satisfaction.[1,2] However, some patients with multifocal IOL implantation complain of visual discomfort postoperatively, such as waxy vision, photic phenomena, and blurred vision.[3-5] Postoperative residual ametropia and residual astigmatism are considered to be the main causes of dissatisfac-

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tion after multifocal IOL implantation.[4,5] Therefore, it is important to minimize residual refractive errors and astigmatism to improve patient satisfaction after multifocal IOL implantation. It is also important to accurately assess the postoperative refractive state to identify the cause of patient dissatisfaction.

Subjective manifest refraction is the gold standard for assessing the postoperative refractive state after cataract surgery.[6] Autorefraction has been reported to have high agreement with subjective manifest refraction in the phakic eye and in pseudophakia with monofocal IOLs.[7,8] Previous studies have also reported that autorefraction shows good agreement and correlation with manifest refraction in assessing the postoperative refractive state of eyes that have received diffractive multifocal IOL implants.[9,10] Therefore, it is possible to begin the postoperative refractive state assessment using autorefraction in eyes with diffractive multifocal IOLs.[7,10] In contrast, several prior studies describe the decreased accuracy of autorefraction for eyes with refractive multifocal IOLs.[10-12]

Recently, a new type of refractive multifocal IOL was commercially introduced, the Precizon Presbyopic NVA 570 A1 (Ophtec BV). The Precizon Presbyopic IOL has 11 distinct segments for far and near distances (**Figure A**, available in the online version of this article, and **Table 1**). The first near add segment starts at 1.4 mm and ends at 2.6 mm from the IOL optic center. Assuming that collimated (ie, parallel) rays enter the eye, most light from the outside reaches the retina through the central far segment, and the first near add segment contributes when the pupil size becomes 2.6 mm or slightly larger.[13] In this situation, it seems that the IOL power in the horizontal meridian would be greater than that in the vertical meridian for a horizontally implanted Precizon Presbyopic IOL. This results in an against-the-rule (ATR) instrument astigmatism, and vice versa for vertical implantation (**Figure A**). As will be discussed later, eyes with a vertically implanted Precizon Presbyopic IOL showed with-the-rule (WTR) astigmatism and eyes with a horizontally implanted Precizon Presbyopic IOL showed ATR astigmatism under autorefraction measurement in many of our cases. However, there have been no reports regarding the reliability of autorefraction for the Precizon Presbyopic IOL and for IOL-induced astigmatism, in terms of its dependence on the orientation of the IOL. Therefore, we conducted a retrospective case-control study and an experimental ray-tracing simulation study to evaluate the astigmatism induced by the Precizon Presbyopic IOL depending on the orientation of the first near segment. We also evaluated its optical performance by using an integrated ray-tracing simulation.[14]

TABLE 1
Characteristics of the Precizon Presbyopic NVA Intraocular Lens (Ophtec BV)

Parameter	Value/Description
Material	Hybrid hydrophobic/hydrophilic monomers, ultraviolet filtering HEMA/EOEMA copolymer
Refractive index	1.46
Abbe number	47
Optic type	Aberration negative (-0.11 μm)
Optic size, mm	6
Overall length, mm	12.5
Haptic design	Open modified C-loops with offset-shaped haptics
Haptic angulation, degrees	0

PATIENTS AND METHODS

STUDY POPULATION

This retrospective case-control study was approved by the Institutional Review Board of the Korea National Institute for Bioethics Policy and that of Korea University Ansan Hospital, Gyeonggi-do, Korea (IRB numbers 2019-2100-003 and 2019AS0214, respectively). All research and data collection adhered to the tenets of the Declaration of Helsinki and to good clinical practices.

The medical records of 80 eyes from 40 patients with cataracts were retrospectively reviewed. All patients had undergone uncomplicated phacoemulsification and Precizon Presbyopic NVA 570 A1 IOL implantation at Korea University Ansan Hospital or Joeunnun Vision Clinic between January 2018 and June 2019. Inclusion criteria were: those who had 2.10 diopters (D) or less of corneal astigmatism according to the IOLMaster 500 (Carl Zeiss Meditec); those who had regular corneal astigmatism according to the measurement of a single Scheimpflug camera (Pentacam; Oculus Optikgeräte GmbH); and those who had 0.5 mm or less of kappa distance in the operated eye. Exclusion criteria were: patients who had undergone additional refractive surgeries to correct residual ametropia; those who had intraoperative or postoperative complications; those who had a history of previous ocular surgery (eg, penetrating keratoplasty or refractive surgery); and those who had a corrected distance visual acuity (CDVA) of worse than 20/25 in the operated eye after cataract surgery.[15]

PATIENT EXAMINATION

Each patient underwent a comprehensive preoperative ophthalmic examination. This examination included the following: automated refraction and keratometry

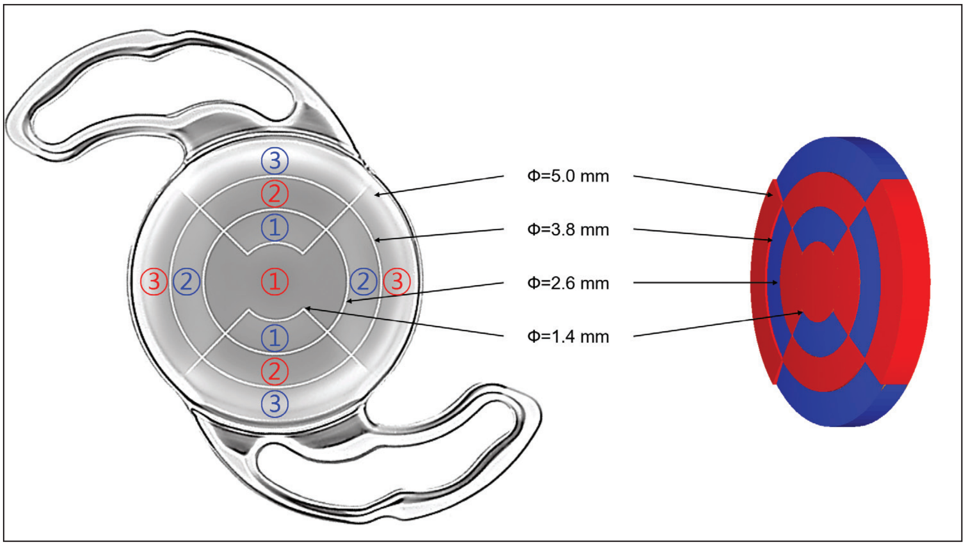

Figure 1. Precizon Presbyopic NVA intraocular lens (Ophtec BV) modeled using Advanced Systems Analysis Program software (Breault Research Program, Inc).

measured with an autorefractor/keratometer (ARK-700A; Nidek Co); slit-lamp biomicroscopy; noncontact specular microscopy (SP-3000P; Topcon Corporation); single Scheimpflug imaging; optical biometry using the IOLMaster 500; and a funduscopic examination. The IOL power was calculated using the SRK/T and Haigis formulas. The A-constant was 118.6 in the SRK/T formula. The a_0, a_1, and a_2 constants used in the Haigis formula were 0.567, 0.123, and 0.159, respectively.

We tested manifest refraction (with trial lenses), autorefraction (with an autorefractor/keratometer), and corneal topography (using a single Scheimpflug camera) between 4 and 8 weeks postoperatively. We also measured the monocular and binocular postoperative uncorrected distance visual acuity (UDVA) and CDVA at 4 m using a logMAR chart or Snellen chart (Hae Sung Medical Company), and uncorrected near visual acuity (UNVA) at 40 cm using a near vision chart (Johnson & Johnson Vision).[16] After the manifest refraction test, a lens was placed in front of the eye and binocular distance-corrected defocus curves were measured between +1.00 and -4.00 D in steps of 0.50 D.[17,18]

IOL-induced astigmatism was defined as the vectorial difference between the total corneal astigmatism and the ocular astigmatism. The total corneal refractive power astigmatism in the 4-mm zone, as measured by a single Scheimpflug camera, was used as the total corneal astigmatism. Refractive astigmatism, which was measured by autorefraction and manifest refraction, was used as the ocular astigmatism. IOL-induced astigmatism, as measured by autorefraction and manifest refraction, was compared according to the orientation of the first near segment of the Precizon Presbyopic IOL implantation, as follows: a vertical orientation (first near segment at 90 ± 30 degrees; **Figure AA**) and a horizontal orientation (first near segment at 180 ± 30 degrees; **Figure AB**). The orientation of the first near segment of the Precizon Presbyopic IOL was confirmed by checking the shape of the first near segment with a slit-lamp biomicroscope with or without pupil dilation between 4 and 8 weeks postoperatively.

Surgical Technique

Phacoemulsification with IOL implantation was performed by one of two experienced surgeons (YE and J-HK). Under topical anesthesia using 0.5% proparacaine hydrochloride (Paracaine; Hanmi Pharm or Alcaine; Alcon Laboratories, Inc), a 2.2- or 2.75-mm clear corneal incision was made. A continuous curvilinear capsulorhexis was created with a 26-gauge needle and continuous curvilinear capsulorhexis forceps. A standard phacoemulsification technique was used. A preloaded capsular tension ring (RingJect System; Ophtec BV) was inserted into the capsular bag before the IOL in-the-bag implantation was performed using an injector system. In some cases, at the surgeon's discretion, a single corneal suture was placed with 10-0 nylon. This suture was removed 1 week after surgery.

Precizon Presbyopic NVA IOL Implanted Eye Modeling

A three-dimensional pseudophakic human eye implanted with a 20.00 D Precizon Presbyopic IOL having near add of +2.75 D was modeled on the basis of the Arizona eye model using Zemax optical design software (Radiant Zemax, LLC) and the Advanced Systems Analysis Program (Breault Research Organization, Inc) (**Table A**, available in the online version of this article and **Figure 1**).[18-20] To compare the optical performance of the Precizon Presbyopic IOL with that of a monofocal IOL, a pseudophakic human eye with a 20.00 D monofocal IOL was also modeled. The Precizon Presbyopic IOL has 11 distinct optical zones in the anterior surface of the optics: 5 for far vision and 6 for near vision.[21] The actual Precizon Presbyopic IOL has varying thicknesses at the near and far segment borders.[22] However, in this study, the Precizon Presbyopic IOL was modeled to have the far and near segments meet perpendicularly without thickness variations at their borders because the patent does not provide accurate information on the design of these borders.[22] The Precizon Presbyopic IOL was placed in two directions varying in the orientation of the first near segment: vertical orientation (**Figure AA**) and horizontal orientation (**Figure AB**).

Integrated Ray-tracing Simulation

Optical Performance According to Target Distance. Monochromatic ray-tracing analysis (light wavelength: 555 nm) was performed and more than 100 million rays were traced for each case to produce reliable results. Lambertian light sources of Snellen E and M shapes were designed to have 7.5 cycles per degree at the following distances in front of the eyes: 330, 400, 500, 660, 800, 990, 1,320, 2,000, and 5,000 mm. The entrance pupil diameter was set to 3 mm. Precision ray-tracing was conducted until the rays reached their final surfaces in the eye model. These rays were partially refracted at the optical interface. After ray-tracing was completed, the ray energy distribution on the retina was obtained and analyzed. The detector on the retinal surface was 0.15 × 0.15 mm in size with 300 × 300 pixels (**Table B**, Simulation 1, available in the online version of this article).[23]

Analysis of IOL-Induced Astigmatism. The astigmatism induced by the Precizon Presbyopic IOL was evaluated using ray-tracing simulations in eyes with WTR corneal astigmatism of 0.00, 0.50, and 1.00 cylindrical diopters (CD). This evaluation employed a Lambertian light source and Snellen E and M shapes designed to have 7.5 cycles per degree at distances of 400, 500, and 5,000 mm in front of the eyes (**Table B**, Simulation 2). In addition, modulation transfer function (MTF) analysis was conducted in eyes with WTR corneal astigmatism of 0.00, 0.25, 0.50, 0.75, and 1.00 CD using Lambertian light sources with sine pattern images. These images were designed to have 7.5 cycles per degree at the distances of 500, 1,000, 1,500, 2,000, 2,500, 3,000, 3,500, 4,000, 4,500, and 5,000 mm in front of the eyes. The entrance pupil diameter was set to 3 mm. The detector size on the retinal surface and the number of pixels were the same as those described in **Table B** (Simulation 3). The MTF for each case was compared according to the amount of corneal astigmatism of the model eyes, and the orientation of the first near segment of the Precizon Presbyopic IOL. To obtain an MTF value, the cross-section of a detected sine pattern image on the retinal surface was fitted with a sine wave. Each MTF in the horizontal and vertical directions was calculated from the sine wave fitting. Finally, the root mean square of the MTF (MTF_{RMS}) was obtained in the horizontal and vertical directions using the following formula[24]:

$$MTF = \frac{I_{max}-I_{min}}{I_{max}+I_{min}} \quad MTF_{RMS} = \sqrt{\frac{MTF^2_{Horizontal}+MTF^2_{Vertical}}{2}}$$

Statistical Analysis

Data from all patients were statistically analyzed using the Statistical Package for Social Sciences Statistics Standard 20 (IBM Corporation). Student's *t* tests and Mann–Whitney *U* tests were performed to compare parameters between eyes with vertical and horizontal orientations of the Precizon Presbyopic IOL. To determine study power, a post hoc power analysis was conducted using the means: difference between two dependent means (matched pairs) option of the G*power software package (version 3.1.9.6; Franz Paul). *P* values of less than .05 were considered statistically significant.

RESULTS

Clinical Study

The mean patient age was 56.2 ± 7.7 years (range: 28 to 73 years). Twenty-eight of the 40 patients (70%) were female. The mean implanted IOL power was 20.30 ± 3.00 D (range: 7.50 to 24.00 D). **Table 2** summarizes laterality, preoperative corneal power and astigmatism, anterior chamber depth, and axial length.

The proportion of patients with a monocular UDVA and CDVA of 0.2 logMAR (Snellen 20/32) or better was 99% and 100%, respectively (**Figure 2**). **Figure 3** shows the binocular distance–corrected defocus curves. The best visual acuity of -0.07 logMAR was obtained with a defocus of 0.00 D. The mean second peak visual acuity, 0.05 logMAR, was obtained with a defocus of -2.00 D. The mean visual acuity was greater than 0.2 logMAR between the defocus curves of +1.00 and -2.50 D.

The postoperative mean residual spherical equivalents and cylinder power measured by autorefraction were -1.12 ± 0.52 D and -1.08 ± 0.67 CD, respectively. In contrast, the mean residual spherical equivalent and cylinder power measured by manifest refraction were -0.06 ± 0.34 D and -0.36 ± 0.34 CD, respectively (**Figure 4**).

Of all 80 eyes, 52 had a vertical IOL orientation (first near segment at 90 ± 30 degrees) and 28 eyes had a horizontal IOL orientation (first near segment

TABLE 2

Clinical Characteristics of Studied Patients With Cataract (N = 80)

Parameter	Value[a]	Range
Age (y)	56.2 ± 7.7	28 to 73
Sex, no. (%)		
Male	12 (30)	–
Female	28 (70)	–
Laterality, no. (%)		
Right eye	40 (50)	–
Left eye	40 (50)	–
Corneal power (D), mean ± SD[a]	43.77 ± 1.33	41.11 to 47.18
Corneal astigmatism (D), mean ± SD[a]		
Cylinder power	-0.71 ± 0.38	-2.09 to -0.16
J0	0.14 ± 0.34	–
J45	-0.01 ± 0.18	–
Anterior chamber depth, mean ± SD (mm)[a]	3.37 ± 0.36	2.51 to 4.22
Axial length, mean ± SD (mm)[a]	23.71 ± 1.15	21.43 to 28.08
IOL power, mean ± SD (D)	20.30 ± 3.00	7.50 to 24.00

D = diopters; SD = standard deviation; J0 = Jackson cross-cylinder power at axis 0 and 90 degrees; J45 = Jackson cross-cylinder power at axis 45 and 135 degrees; IOL = intraocular lens

[a]Corneal power, corneal astigmatism, anterior chamber depth, and axial length were measured using the IOLMaster 500 (Carl Zeiss Meditec).

at 180 ± 30 degrees). The mean IOL-induced astigmatism measured by autorefraction was 0.68 ± 0.58 D at 1 degree in the vertical orientation (**Figure BA**, available in the online version of this article) and 1.05 ± 0.81 D at 96 degrees in the horizontal orientation (**Figure BB**). However, the mean IOL-induced astigmatism measured by manifest refraction was 0.14 ± 0.44 D at 171 degrees in the vertical orientation (**Figure CA**, available in the online version of this article) and 0.46 ± 0.40 D at 95 degrees in the horizontal orientation (**Figure CB**). The median magnitudes of IOL-induced astigmatism measured by autorefraction and manifest refraction for the vertical orientation (0.84 and 0.50 D, respectively) were significantly smaller than the corresponding measurements for the horizontal orientation (1.38 and 0.72 D, respectively) (Mann–Whitney *U* test; *P* = .002 and .049, respectively). There was no significant difference in the mean UDVA (0.01 ± 0.08 and 0.03 ± 0.08 logMAR, respectively) and UNVA (0.17 ± 0.13 and 0.14 ± 0.12 logMAR, respectively) between eyes in the vertical and horizontal cases (**Table 3**).

In a post hoc power analysis, the effect size was calculated to be 0.903 based on the IOL-induced astigmatism measured by autorefraction and manifest refraction. The effect size of 0.903 and α of 0.05 with 80 eyes corresponded to a statistical power of 1.00.

Integrated Ray-tracing Simulation

Optical Performance According to Target Distance. In ray-tracing simulations, a monofocal IOL provided sharp images at far distance but blurry images up close. In contrast, the Precizon Presbyopic IOL provided sharp images at both far and near distances (**Figure 5**). The sharpest images were observed at 500 and 5,000 mm in both orientations. These results are in good agreement with the defocus curves collected in the clinical study.

Analysis of IOL-Induced Astigmatism. According to the autorefraction results of this study, it is expected that the horizontal orientation of the Precizon Presbyopic IOL induces ATR astigmatism. This astigmatism can theoretically correct WTR corneal astigmatism, resulting in the sharpest possible images in eyes with WTR corneal astigmatism and horizontally implanted IOLs. However, the ray-tracing simulation results showed that images blurred increasingly as the corneal astigmatism increased in both vertically and horizontally implanted IOLs (**Figure D**, available in the online version of this article). Also, MTF analysis showed that the highest MTF_{RMS} values (0.44 and 0.45, respectively, at the distance of 500 mm and 0.62 and 0.62, respectively, at the distance of 5,000 mm) were obtained in eyes without corneal astigmatism in both vertically and horizontally implanted IOLs (**Figure E**, available in the online version of this article).

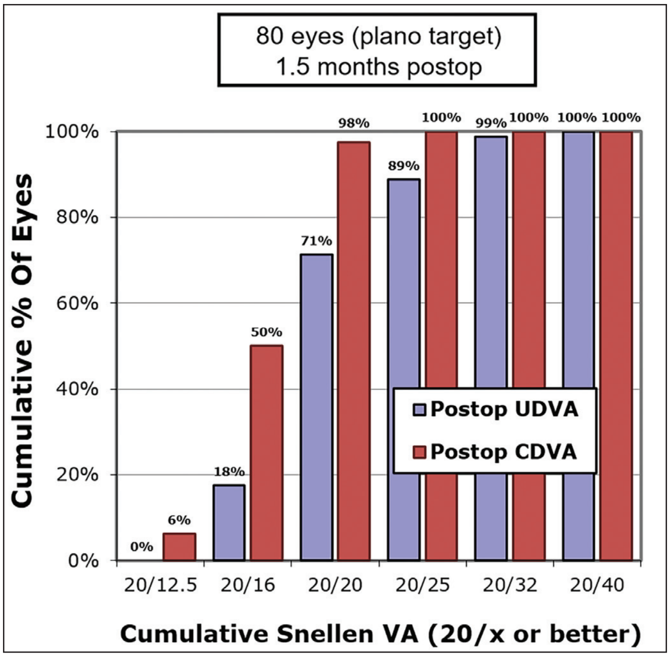

Figure 2. Distribution of postoperative monocular uncorrected (UDVA) and corrected (CDVA) distance visual acuities measured 4 to 8 weeks after cataract surgery in the retrospective study on the optical performance of the Precizon Presbyopic NVA intraocular lens (Ophtec BV). D = diopters

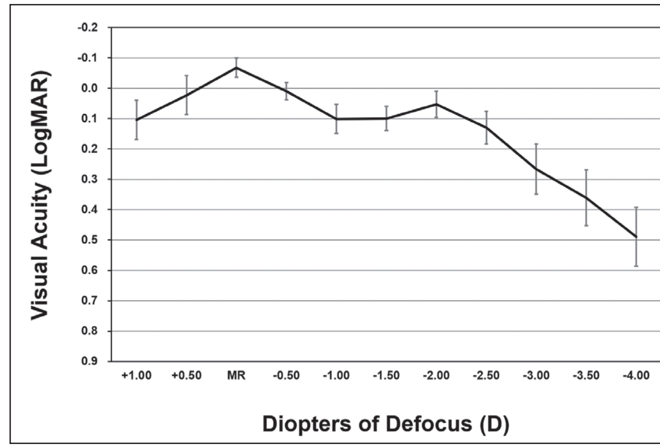

Figure 3. Mean binocular distance–corrected defocus curves measured 4 to 8 weeks after cataract surgery. D = diopters

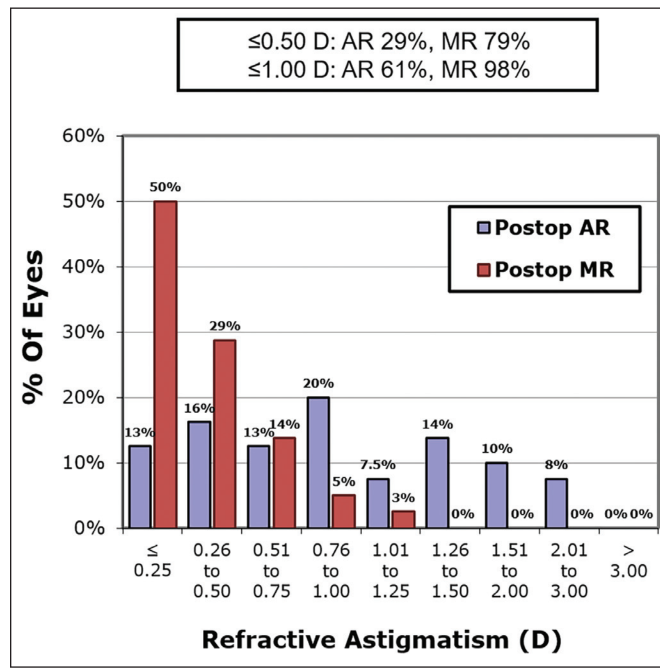

Figure 4. Refractive cylinder measured by autorefraction (AR) and manifest refraction (MR). D = diopters

DISCUSSION

This study sought to investigate whether implantation with the Precizon Presbyopic IOL causes astigmatism and whether difference in the orientation of the first near segment causes a difference in the type of astigmatism. We found that vertical implantation with the IOL induced WTR astigmatism and that horizontal implantation with the IOL induced ATR astigmatism when astigmatism was measured by either autorefraction or manifest refraction. However, manifest refraction yielded astigmatism measurements approximately half those of the corresponding autorefraction measurements. In addition, the ray-tracing simulation results demonstrated that implantation of the Precizon Presbyopic IOL in the vertical or horizontal direction could not correct corneal astigmatism sufficiently. The MTF_{RMS} values were highest for eyes without corneal astigmatism in cases of both vertical and horizontal implantation. Combining the clinical and ray-tracing simulation results, it seems that Precizon presbyopic IOL-induced astigmatism is clinically insignificant.

Optical ray-tracing is a method in which the paths of light rays in an optical system are calculated to solve and analyze a problem. A representative example of the use of ray-tracing in the ophthalmic area was its use to reveal the fundamental mechanism of negative dysphotopsia in the pseudophakic eye; Holladay et al[25] conducted ray-tracing to address the cause of negative dysphotosia and showed that the ray-tracing finding was consistent with clinical observations. The current study was designed to evaluate the astigmatism induced by an IOL according to the orientation of that IOL, and in this study the ray-tracing finding was consistent with clinical observations. The astigmatism induced by the Precizon Presbyopic IOL as observed by both manifest refraction and ray-tracing was much smaller than that observed by autorefraction. Therefore, in clinical practice, autorefraction should not be used to evaluate astigmatism in eyes implanted with the Precizon Presbyopic IOL.

Autorefraction is not suitable for evaluating the postoperative refractive state in eyes with a refractive multifo-

TABLE 3

Comparison of the Clinical Characteristics Between Eyes With Vertical (90 ± 30 Degrees) and Horizontal (180 ± 30 Degrees) Orientation of the First Near Segment of the Precizon Presbyopic IOL (N = 80)

Parameter	Vertical Orientation (n = 52)[a]	Horizontal Orientation (n = 28)[a]	P^b
Corneal power (D)[c]	43.87 ± 1.10	43.60 ± 1.67	.384
Corneal astigmatism (D)[c]			
Cylinder power	-0.67 ± 0.38	-0.81 ± 0.37	.118
J0	0.09 ± 0.34	0.24 ± 0.33	.063
J45	-0.02 ± 0.17	-0.01 ± 0.20	.784
Anterior chamber depth (mm)[c]	3.37 ± 0.35	3.36 ± 0.38	.953
Axial length (mm)[c]	23.63 ± 0.93	23.86 ± 1.48	.462
IOL power (D)	20.40 ± 2.40	20.10 ± 3.90	.726
UDVA (logMAR)	0.01 ± 0.08	0.03 ± 0.08	.329
UNVA (logMAR)	0.17 ± 0.13	0.14 ± 0.12	.339

IOL = intraocular lens; D = diopters; J0 = Jackson cross-cylinder power at axis 0 and 90 degrees; J45 = Jackson cross-cylinder power at axis 45 and 135 degrees; UDVA = uncorrected distance visual acuity; UNVA = uncorrected near visual acuity

[a]Data are presented as mean ± standard deviation.

[b]Student t test.

[c]Corneal power, corneal astigmatism, anterior chamber depth, and axial length measured by the IOLMaster 500 (Carl Zeiss Meditec).

The Precizon Presbyopic IOL is manufactured by Ophtec BV.

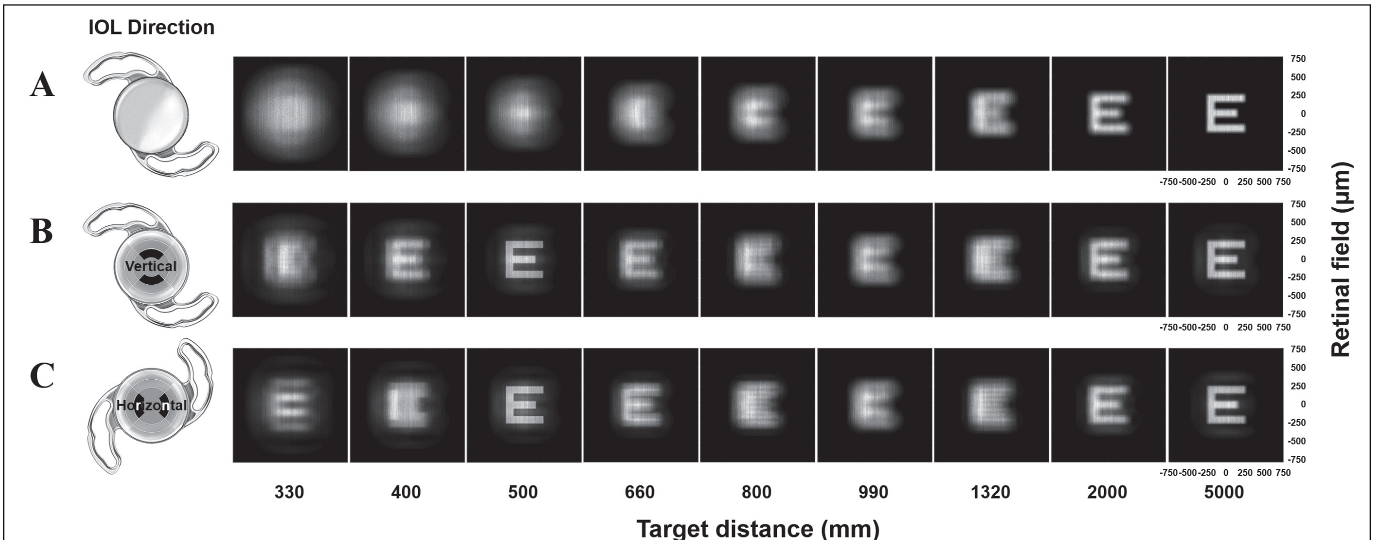

Figure 5. Retinal images of pseudophakia using a monofocal or Precizon Presbyopic intraocular lens (IOL) (Ophtec BV) in integrated ray-tracing simulations (using Lambertian source E targets with various target distances and two IOL implantation directions). (A) Monofocal IOL. (B) Precizon Presbyopic IOL with vertically oriented first near segment. (C) Precizon Presbyopic IOL with horizontally oriented first near segment.

cal IOL; however, it does have some utility in eyes with a diffractive multifocal IOL.[9,10,12] In this study, there was a difference between residual spherical equivalents and astigmatism as measured by autorefraction and manifest refraction. The refractive astigmatism measured by manifest refraction was much smaller than that measured by autorefraction for eyes with Precizon Presbyopic IOLs. Similarly, a previous study of eyes with the Lentis Mplus X IOL, a rotationally asymmetric refractive multifocal IOL, found a low correlation between the astigmatic components of autorefraction and manifest refraction.[11] In contrast, another previous study found excellent agreement in the refractive astigmatism measured by means of autorefraction and manifest refraction in the evaluation of eyes implanted with the ReZoom lens, a rotationally symmetric refractive multifocal IOL.[12] The optical surface of the ReZoom IOL consists of five concentric refractive zones that are divided into far and near segments. It is therefore believed that rotational symmetry does not induce astigmatism in autorefraction. The focus of the light rays that pass through the far and near segment of rotational asymmetric refractive multifocal IOL varies according to the retinal location. This variability results in instrument astigmatism during autorefraction.

Muñoz et al[12] first described instrument myopia caused by an IOL for the ReZoom refractive multifocal IOL.[10,12] The authors showed that there is poor agreement in spherical equivalents between autorefraction and manifest refraction measurements of eyes with ReZoom refractive multifocal IOLs. In that study, the spherical values and spherical equivalents were more myopic in autorefraction than in manifest refraction. Eyes with radially asymmetric refractive multifocal IOLs also demonstrated more myopia in autorefraction than they did in manifest refraction.[11] Similarly, the mean residual spherical equivalent measured by autorefraction was approximately -1.00 D, whereas that measured by manifest refraction was approximately -0.06 D. For parallel rays entering the eyes, the light that passes through the near add segment of the refractive multifocal IOL focuses in front of the retinal plane. This can provide false, more myopic values in autorefraction for eyes with refractive multifocal IOLs.

The Precizon Presbyopic 570A0 IOL (Ophtec BV) has been shown to provide excellent visual performance at both far and near distances.[21] In particular, the Precizon Presbyopic IOL applies continuous transitional focus technology to the boundary between the far and near segments of the optical surface, which results in a continual focus from far to near distances.[21] In the binocular defocus curve of this study, the Precizon Presbyopic IOL provided visual acuity of 0.2 logMAR or more from far to near of 40 cm (defocus of -2.50 D). However, we designed the Precizon Presbyopic IOL to have perpendicular boundaries between the far and near segments for ray-tracing simulation because of the unavailability of accurate information on the far and near segment border design. For this reason, the ray-tracing simulation in this study could not show the continual focus from far to near, unlike the clinical study results. Despite this limitation, our study demonstrated that the Precizon Presbyopic IOL provided excellent visual function at both far and near distance. In addition, the difference between the far and near segment border design did not affect the evaluation of the Precizon Presbyopic IOL-induced astigmatism in the ray-tracing analysis.

There may be controversy regarding which measurement best represents the total corneal astigmatism, although the accuracy of total corneal astigmatism measurements collected with a single Scheimpflug camera is higher than that of estimates based on anterior corneal astigmatism.[26] A previous study demonstrated that the repeatability of the 4-mm diameter analysis of the total corneal refractive power was higher than that of the 3-mm diameter analysis in the Pentacam.[27] In addition, the 4-mm zone of total corneal refractive power of the Pentacam was the most consistent with the actual total corneal astigmatism measured in normal eyes and eyes that had previous myopic keratorefractive surgery.[28,29] Therefore, the 4-mm diameter analysis of the postoperative total corneal refractive power measured with the Pentacam was selected and used in this study. However, there is a possibility of errors in the postoperative astigmatism measurements, including the manifest refraction in 0.25 D steps, the time of measurement, and the accuracy of single Scheimpflug measurements, due to the retrospective manner of this study.[30,31] In fact, there was a significant difference in the astigmatism induced by the Precizon Presbyopic IOL between eyes having the vertical or horizontal IOL orientation, although the sample was small. Thus, a well-designed randomized prospective study might be needed to eliminate these effects.

The Precizon Presbyopic IOL provides good optical performance at both far and near distances. Autorefraction demonstrated that vertical orientation of the first near segment of the Precizon Presbyopic IOL implantation induced WTR astigmatism and horizontal orientation induced ATR astigmatism. However, the actual astigmatism measured by manifest refraction was much smaller than that measured by autorefraction. In addition, ray-tracing simulation results demonstrated that the astigmatism caused by the Precizon Presbyopic IOL is clinically insignificant.

AUTHOR CONTRIBUTIONS

Study concept and design (YE, SKY, JNC, J-HK); data collection (YE, SKY, EGY, JNC); analysis and interpretation of data (YE, SKY, JNC, DR, DWK, J-HK, JSS, S-WK, HMK); writing the manuscript (YE); critical revision of the manuscript (YE, SKY, EGY, JNC, DR, DWK, JSS, S-WK, HMK); statistical expertise (YE, SKY, JNC, J-HK); administrative, technical, or material support (YE, SKY, EGY, DR, J-HK, S-WK); supervision (YE, SKY, DR, DWK, JSS, S-WK, HMK)

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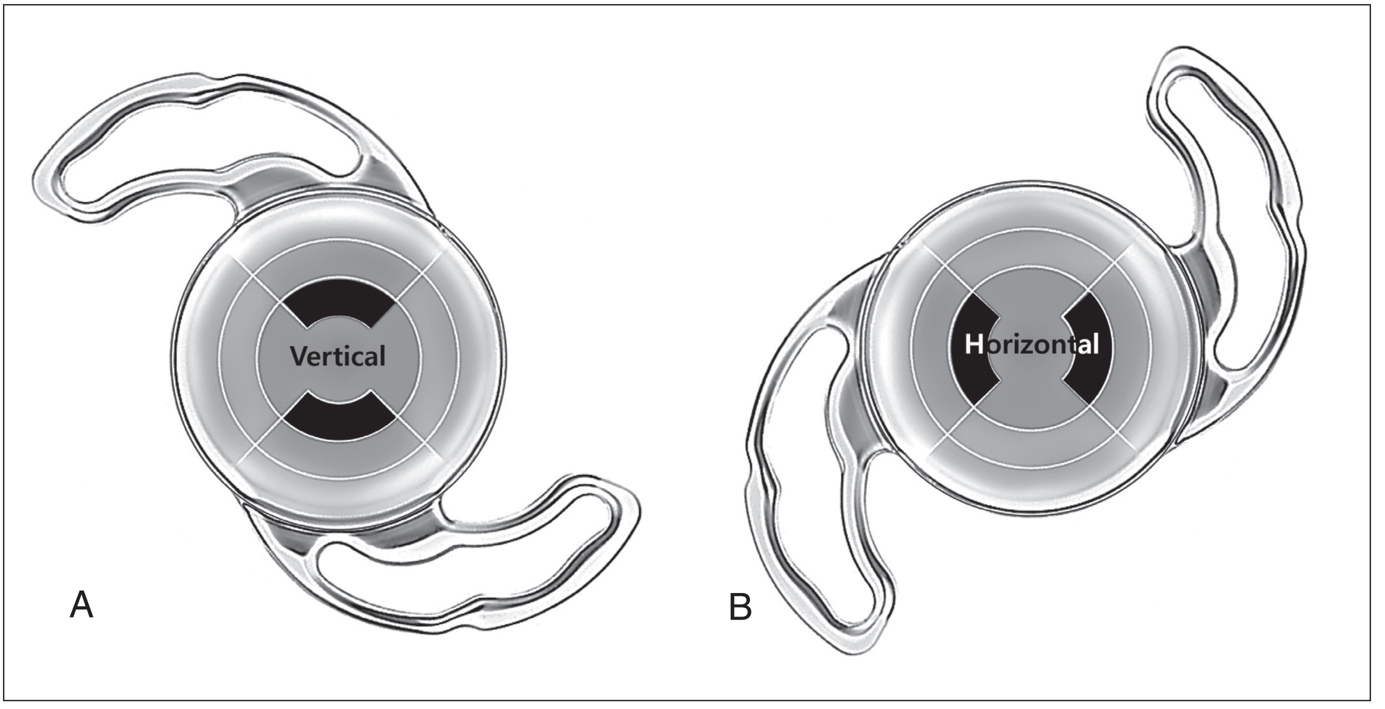

Figure A. Two Precizon Presbyopic NVA intraocular lens (Ophtec BV) implantation directions according to the orientation of the first near segment of the lens. (A) Vertical orientation. (B) Horizontal orientation.

TABLE A

Nominal Values Used in Pseudophakic Eye Models Including the Precizon Presbyopic IOL (Ophtec BV)

Surface	Radius (mm)	Thickness (mm)	Refractive Index (λ = 555 nm)	Conic Constant	4th Order	6th Order
Anterior cornea	7.800	0.550	1.376	-0.250	–	–
Posterior cornea	6.500	3.550	1.336	-0.250	–	–
Pupil	–	1.000	1.336	–	–	–
Anterior IOL1	14.099	1.000	1.460[a]	0.979	-8.593e-4	-8.011e-6
Anterior IOL2	10.721	1.000	1.460[a]	0.548	-9.108e-4	-1.153e-5
Posterior IOL	-11.000	18.316	1.337	–	–	–
Retina	-13.500	–	1.336	–	–	–

IOL = intraocular lens; anterior IOL1 = region having 5 zones for far vision; anterior IOL2 = region having 6 zones for near vision
[a]Abbe number = 47.

TABLE B

Experimental Simulation Study Parameters Used in Ray-tracing Simulations for Determining Optical Performance

Parameter	Simulation 1	Simulation 2	Simulation 3
Light source			
Wavelength (nm)	555	555	555
Type	Lambertian source	Lambertian source	Lambertian source
Shape	Snellen E	Snellen E	Sine pattern
Rotation	0°, 90°	0°, 90°	0°, 90°
CPD	7.5	7.5	7.5
Distance (mm)	330, 400, 500, 660, 800, 990, 1,320, 2,000, 5,000	400, 500, 5,000	500, 1,000, 1,500, 2,000, 2,500, 3,000, 3,500, 4,000, 4,500, 5,000
No. of rays[a]	180,000,000	180,000,000	320,000,000
Corneal astigmatism (D)[b]	0.00	0.00, 0.50, 1.00	0.00, 0.25, 0.50, 0.75, 1.00
Pupil diameter (mm)	3	3	3
IOL orientation[c]	Horizontal and vertical	Horizontal and vertical	Horizontal and vertical
Detector			
Size (mm)	0.15 × 0.15	0.15 × 0.15	0.15 × 0.15
No. of pixels	300 × 300	300 × 300	300 × 300

simulation 1 = optical performance analysis; 2 = intraocular lens–induced astigmatism analysis; simulation 3 modulation transfer function analysis; CPD = cycles per degree; D = diopters; IOL = intraocular lens

[a]Number of rays traced in each simulation.

[b]With-the-rule corneal astigmatism.

[c]The Precizon Presbyopic IOL (Ophtec BV) was simulated to have two different orientations of the first near segment: horizontal (180 degrees) and vertical (90 degrees).

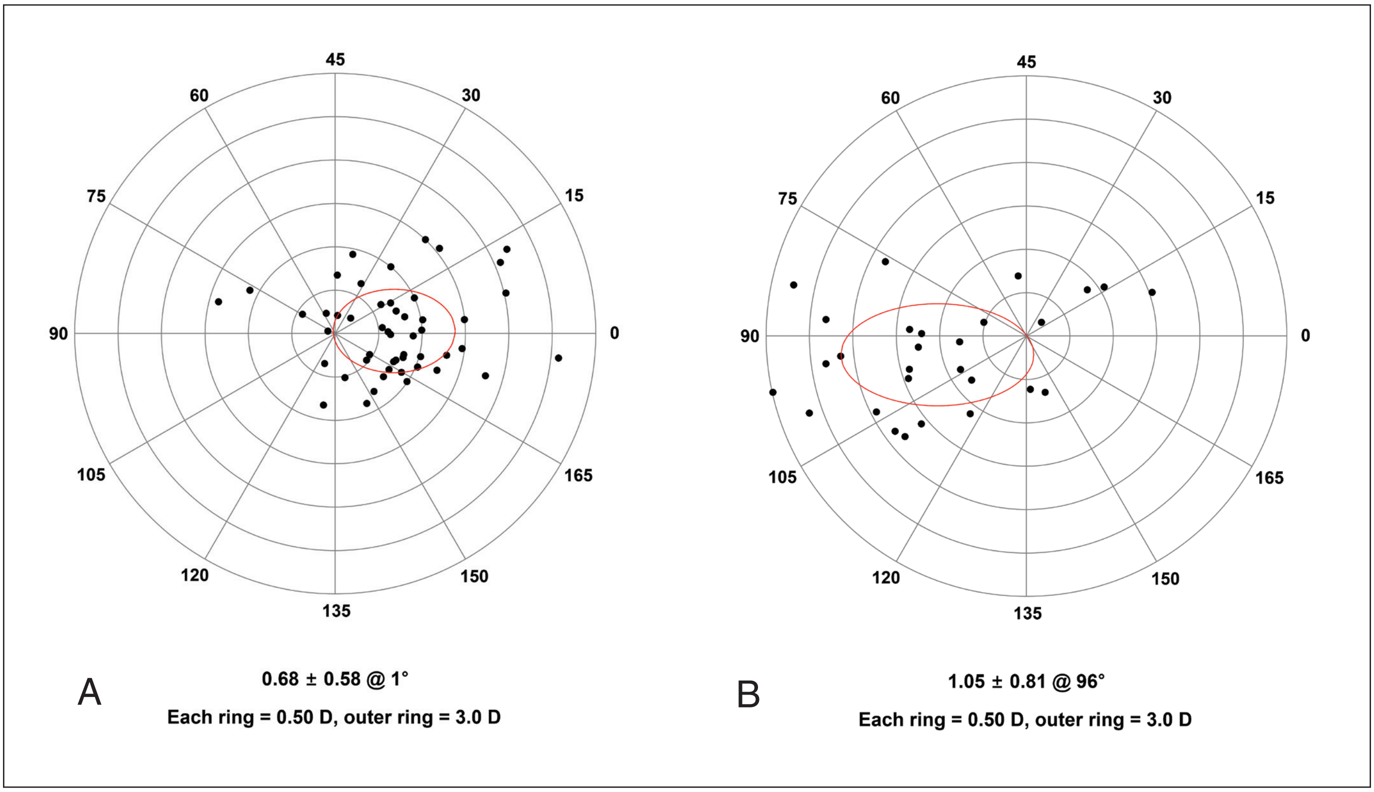

Figure B. Double-angle plots of the vector difference between the postoperative total corneal astigmatism measured using a single Scheimpflug camera and the refractive astigmatism measured by autorefraction. (A) Vertical and (B) horizontal orientation of the first near segment of the Precizon Presbyopic intraocular lens (Ophtec BV). D = diopters

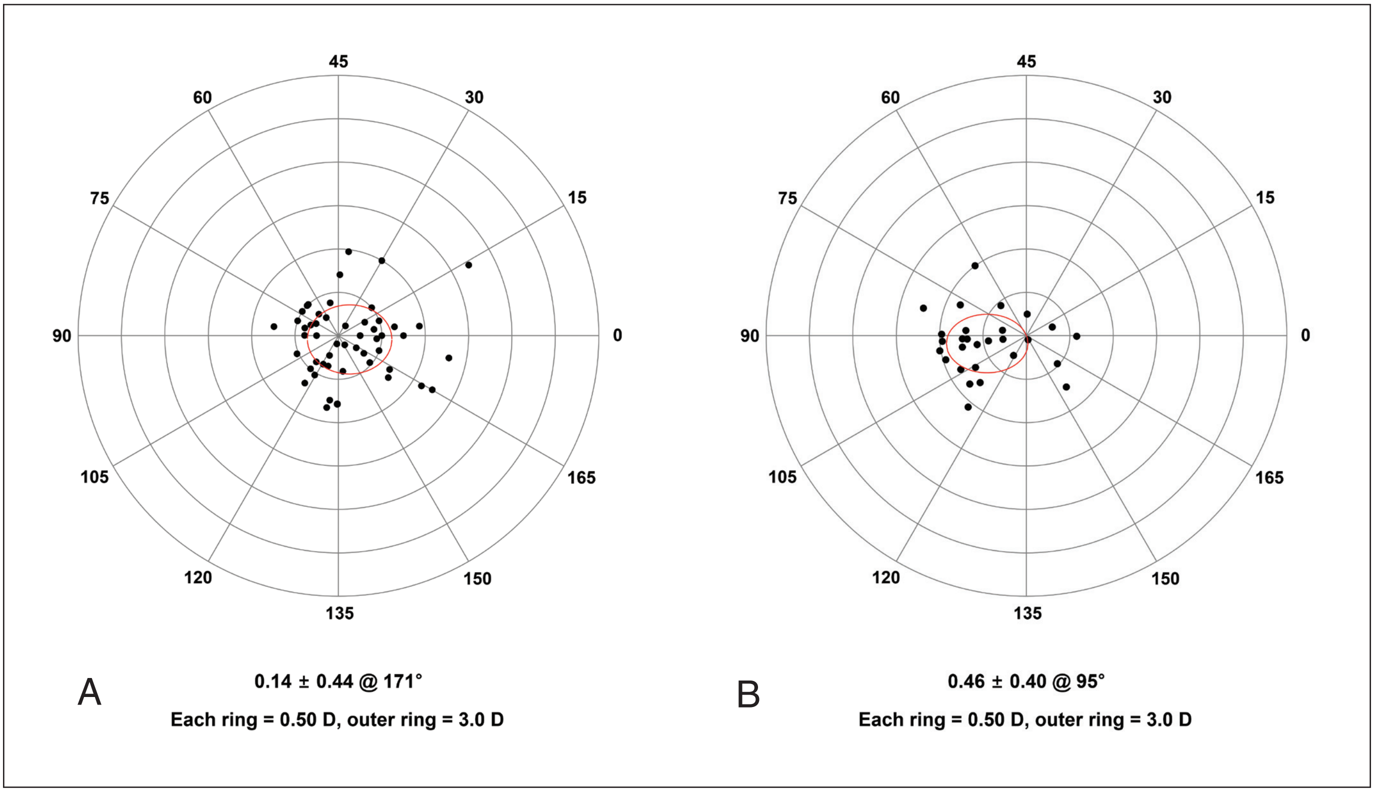

Figure C. Double-angle plots of the vector difference between the postoperative total corneal astigmatism measured using a single Scheimpflug camera and the refractive astigmatism measured by manifest refraction. (A) Vertical and (B) horizontal orientation of the first near segment of the Precizon Presbyopic intraocular lens (Ophtec BV). D = diopters

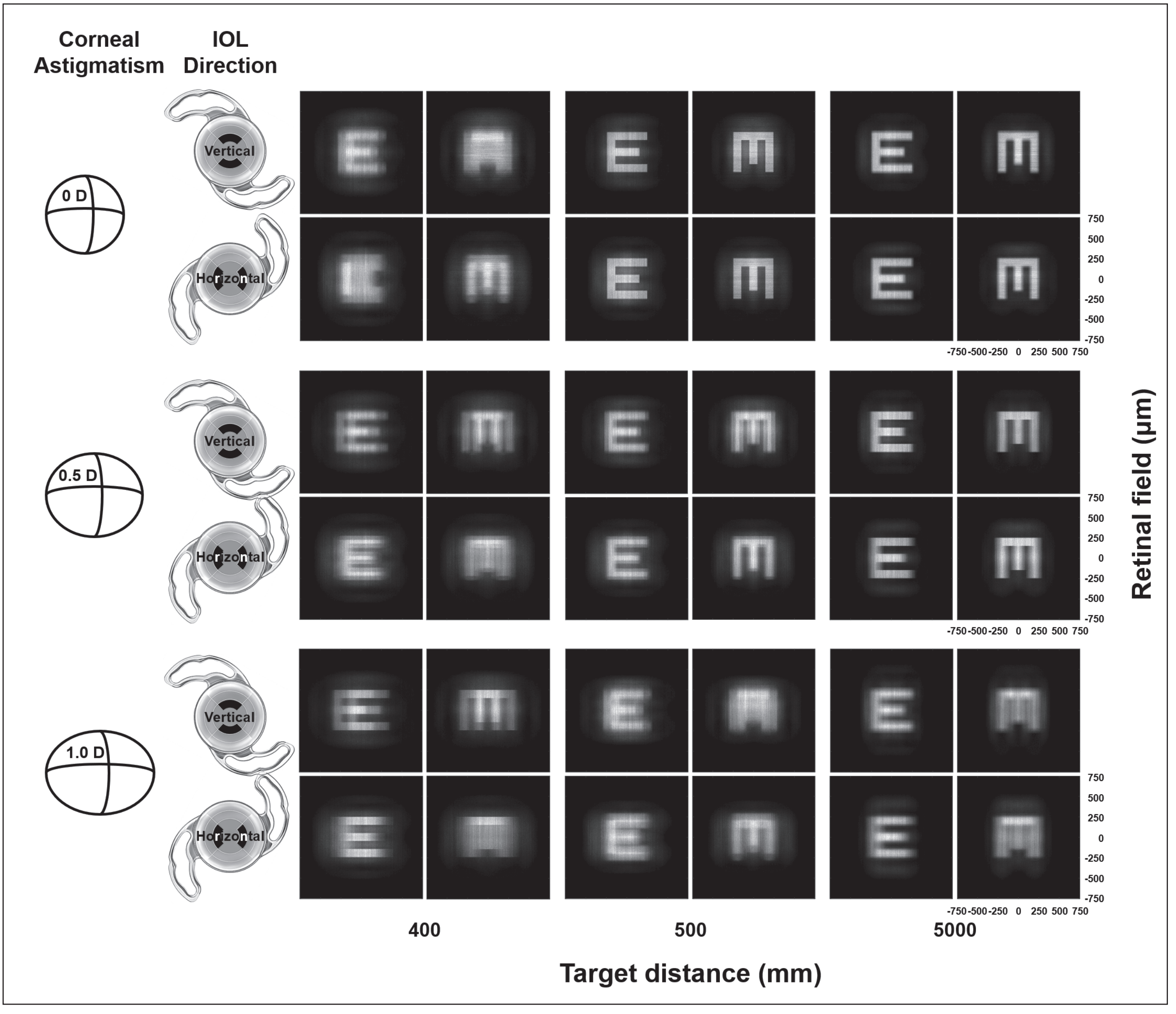

Figure D. Retinal images of pseudophakia with a Precizon Presbyopic intraocular lens (IOL) (Ophtec BV) in an integrated ray-tracing simulation using Lambertian source E and M targets with various target distances, various with-the-rule corneal astigmatism, and two intraocular lens implantation directions. D = diopters

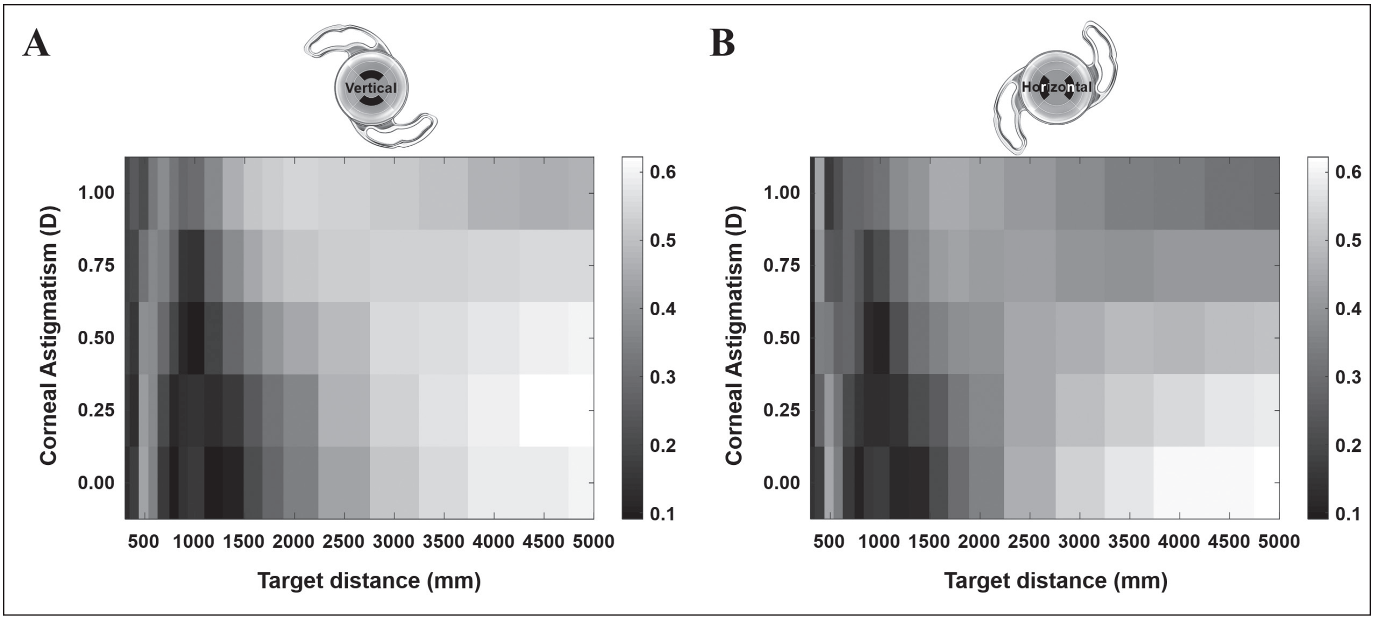

Figure E. Root mean square of the modulation transfer function of pseudophakia with a Precizon Presbyopic intraocular lens (IOL) (Ophtec BV) for various target distances, various with-the-rule corneal astigmatism, and two intraocular lens implantation directions. (A) Precizon Presbyopic IOL with vertically oriented first near segment. (B) Precizon Presbyopic IOL with horizontally oriented first near segment. D = diopters