A Ray Tracing Approach to Calculate Toric Intraocular Lenses

Peter C. Hoffmann, MD; Jochen Wahl, MD; Werner W. Hüttz, MD; Paul-Rolf Preußner, MD, PhD

ABSTRACT

PURPOSE: To quantify the precision of astigmatic correction in routine cataract surgery with toric intraocular lenses (IOLs) and to evaluate the predictability of keratometric and anterior/posterior topographic measurement for the improvement of the overall accuracy.

METHODS: Seventy-eight eyes of 56 patients were implanted with toric IOLs. Data acquired by the Lenstar optical biometer (Haag-Streit, Bern, Switzerland) and TMSS topography (Tomey, Nagoya, Japan) were processed with the ray tracing software Okulix (Tedics, Dortmund, Germany) to predict the residual refraction. Four different inputs were examined: keratometry only, anterior topography, anterior and posterior topography/tomography, and combination of keratometry only and anterior and posterior topography/tomography. Four weeks postoperatively, the spherical prediction error and the cylindrical prediction error (difference vector between predicted and achieved cylindrical refraction) were determined.

RESULTS: Mean absolute error of spherical prediction error was 0.27 diopter (D). Cylindrical prediction errors were 0.57 D (keratometry only), 0.56 D (anterior topography), 0.56 D (anterior and posterior topography/tomography), and 0.50 D (combination of keratometry only and anterior and posterior topography/tomography). Differences between intraocular lens groups were statistically significant (Friedman test, $P < .05$).

CONCLUSION: The combination of keratometry and anterior and posterior topography/tomography of anterior and posterior surface yielded the best results for toric IOL power calculations.


There are different ways to calculate the spherical and cylindrical power of a toric intraocular lens (IOL). Online calculators of different manufacturers are popular but may be not transparent to the user and sometimes even flawed by wrong assumptions (e.g., a constant and/or skewed ratio of IOL and corneal plane powers). In addition, there is an ongoing discussion on whether to focus on keratometric or topographic data for the prediction of the surgical outcome.

The goal of this study was to determine the precision in predicting astigmatic correction in the clinical practice and to clarify whether automated keratometry or topography with or without posterior corneal radii generate the best results.

PATIENTS AND METHODS

Eighty eyes of 58 patients were implanted with a toric IOL during routine cataract surgery between January and October 2011. Patients with neovascular or edematous macular disease of any etiology were excluded.

Four lens designs were used, including the Alcon SN60TT (Alcon Laboratories, Inc., Fort Worth, TX), the Alcon Toric IQ (Alcon Laboratories, Inc), the AMO Tecnis Toric (Abbott Medical Optics, Santa Ana, CA), and the Carl Zeiss AT Torbi 709M (Carl Zeiss Meditec, Jena, Germany). Table A (available as supplemental material in the PDF version of this article) shows the properties of the IOLs used. All surgeries were performed by two experienced surgeons using 2.2-mm coaxial phacoemulsification with CMP Megatip equipment (Geuder, Heidelberg, Germany). All incisions were placed temporally (180° in right eyes, 0° in left eyes). Intraoperative retinoscopy was used to check the axis orientation as described.
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previously. There was a selection bias with respect to the IOL models due to the availability of spherical and cylindrical power levels (Figure A, available as supplemental material in the PDF version of this article).

Prior to IOL calculation, the eye was measured with the Lenstar V2 and V3 (Haag-Streit, Bern, Switzerland) for axial length, central corneal thickness, internal anterior chamber depth, crystalline lens thickness, retinal thickness, corneal radii, and horizontal corneal diameter. Version 3 of the software sped up examination time but did not introduce changes to the measurement algorithms. Furthermore, TMS5 topography (Tomey, Nagoya, Japan) including Placido and spatially resolved pachymetry from Scheimpflug images was performed. The data sets were imported into the ray tracing package Okulix V8.68 (Tedics, Dortmund, Germany). This software predicts residual spherocylindrical refraction after implantation of a given toric IOL. Because full-aperture ray tracing is solely based on Snell’s law, problems arising from using Gaussian optics (eg, conversion of effective power in different planes) are avoided. IOL “constants” used in traditional IOL formulas built into the Lenstar software are not needed; the internal database contained the necessary physical properties of the IOL models used.

For the purpose of IOL calculation, Lenstar cylinder and axis were taken “as is.” Topography raw data were processed in Okulix using a four-dimensional fit described previously.

We evaluated the prediction of spherical equivalent power and cylindrical prediction. Spherical prediction error was defined as the difference between attempted and achieved manifest refraction (spherical equivalent). For calculation of absolute errors, any systematic offsets of the used IOLs were zeroed, which is logically equivalent to the usual procedure of optimizing formula constants. Cylindrical prediction error was defined as the absolute vector difference between predicted (based on corneal cylinder and toric IOL in true physical orientation) and achieved cylindrical refraction. This vector calculation is important because simply subtracting cylinder values will not take care of the two-dimensional nature of the physical entity.

We evaluated four different inputs for corneal radii and astigmatism into the software: (1) Lenstar keratometry, (2) topography of the anterior surface, (3) topography of anterior surface and tomography of anterior and posterior surface combined, and (4) the arithmetic mean of keratometry and combined tomography.

Surgically induced astigmatism was not measured in this patient cohort but was carefully investigated in a former study using the same surgical technique and found to be clinically irrelevant. In a series of 240 eyes measured with the Lenstar device, we found a mean flattening of 0.01 ± 0.33 diopters (D) in the incised meridian 1 year postoperatively using the Naeser method. This is close to and not statistically different (paired t test, P > .05) from the measuring tolerance between IOLMaster (Carl Zeiss Meditec) and Lenstar, which was equivalent to a surgically induced astigmatism of 0.00 ± 0.31 D.

For comparison purposes, we also calculated target induced astigmatism and surgically induced astigmatism as described by Alpins. Double angle scatterplots as suggested by Holladay et al. were used to illustrate preoperative and postoperative astigmatic data.

RESULTS

Mean achieved manifest refraction was +0.01 sphere -0.41 cylinder. Mean distance corrected visual acuity was 0.06 ± 1.1 logMAR equivalent to 20/23 Snellen. Spherical prediction error is shown in Table B (available as supplemental material in the PDF version of this article). Mean spherical prediction error was -0.03 D for the Alcon SN60TT (Alcon Laboratories, Inc.), -0.08 D for the Alcon Toric IQ (Alcon Laboratories, Inc.), +0.24 D for the AMO Tecnis Toric (Abbott Medical Optics), and +0.25 D for the Carl Zeiss AT Torbi 709M (Carl Zeiss Meditec). After adjustment of systematic offsets for each type of IOL, mean spherical prediction error was 0.00 D. Mean absolute error was 0.27 D and median absolute error was 0.23 D.

In eyes with a distance corrected visual acuity of 20/20 or better (n = 42), spherical prediction error was much smaller: ±0.5 D in 83% and ±1.0 D in 99% of cases in the whole group and 93% and 100%, respectively, in the high visual acuity group.

The average corneal cylinder was 2.23 ± 1.12 D measured by keratometry, 2.08 ± 1.10 D by anterior surface topography, and 2.04 ± 1.07 D by anterior and posterior surface topography/tomography.

Mean absolute difference between planned IOL axis orientation and the axis measured 4 weeks postoperatively was 2.86°. Only one eye (1.25%) had an absolute difference greater than 10°.

The differences between measuring devices are shown in Table 1. Two extreme outliers are the above-mentioned cases with manifest keratoconus.

Figure 1 shows a doubled-angle scatterplot of preoperative astigmatism as measured by the Lenstar (violet) and the postoperative astigmatism as measured by subjective refraction using the cross-cylinder-method (red). Figure 2 shows the same for the single IOL models. With-the-rule-astigmatism (right hand side of the scattergram) was much more common in

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Figure 3 illustrates the cylindrical prediction error as a doubled-angle scatterplot based on four different data inputs. The prediction errors in Figure 3D are significantly smaller than those shown in Figure 3A \((P = .0015\) in the parameter-free Wilcoxon test for paired samples), and they are significantly smaller than those shown in Figure 3B \((P = .032\). Table 2 shows the descriptive statistics. Overall, a combined keratometry and anterior and posterior topography/tomography input yielded the best results. A cylindrical prediction error of 0.5 D or less was noted in 37 eyes (47%) in the keratometry and anterior topography group, 41 eyes (53%) in the anterior and posterior topography/tomography group, and 46 eyes (59%) in the combined group.

For the purpose of comparison with other studies, we also computed the difference between surgically induced astigmatism and target-induced astigmatism. Surgically induced astigmatism was the astigmatism induced by the entire surgical procedure (incision and toric IOL implantation). Target-induced astigmatism was the astigmatic change predicted by the software with the given IOL. The mean difference was 0.29 D with keratometry, 0.30 D with anterior topography, 0.28 D with anterior and posterior topography/tomography, and 0.26 D with combined measurements.

### DISCUSSION

In this study, we found the spherical prediction error to be surprisingly low with the help of crystalline lens thickness data and ray tracing software. Cylindrical prediction error was dependent on the input data used, and a combination of keratometry, topography, and tomography yielded the best results.

In recent studies with large patient cohorts, achievable precision for the spherical equivalent has been well defined for traditional formulas based on IOL Master input and for a modern approach based on Lenstar optical path data including crystalline lens position and thickness. Aristodemou et al.\(^{12}\) found a mean absolute prediction error of 0.37 to 0.48 D depending on the axial length, the IOL model, and the chosen formula in a cohort of 8,108 eyes. In the mean sized eye, typical mean absolute error was 0.43 to 0.46 D in that study. Olsen\(^{13}\) found 0.40 D in a cohort of 1,235 eyes using his personal formula\(^{14}\) based on Lenstar data. Our results compare favorably to these figures. Mean absolute error was only 0.27 D for the whole group and 0.20 D for eyes with distance corrected visual acuity of 1.0 or greater.

Figure 1. Astigmatic correction of all 78 eyes. The preoperative astigmatism calculated from Lenstar (Haag-Streit, Bern, Switzerland) corneal radii (blue) and the postoperative astigmatisms of the manifest refraction (red) are shown in doubled-angle plots.

### TABLE 1

<table>
<thead>
<tr>
<th>Variable</th>
<th>LS-TMSa</th>
<th>LS-TMSa</th>
<th>TMSa-TMSa</th>
<th>LS-TMSa</th>
<th>LS-TMSa</th>
<th>TMSa-TMSa</th>
<th>LS-TMSa</th>
<th>LS-TMSa</th>
<th>TMSa-TMSa</th>
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<td>MAE</td>
<td>0.43</td>
<td>0.50</td>
<td>0.22</td>
<td>5.20</td>
<td>6.01</td>
<td>2.06</td>
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<td>0.73</td>
<td>0.28</td>
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<td>0.57</td>
<td>0.63</td>
<td>0.25</td>
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<tr>
<td>Min</td>
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<td>0.00</td>
<td>0.00</td>
<td>0.11</td>
<td>0.00</td>
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<td>0.08</td>
<td>0.02</td>
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<tr>
<td>Max</td>
<td>1.67</td>
<td>2.00</td>
<td>1.96</td>
<td>28.00</td>
<td>30.50</td>
<td>13.09</td>
<td>1.97</td>
<td>2.21</td>
<td>2.22</td>
</tr>
</tbody>
</table>

\(D = \) diopters; \(LS = \) Lenstar keratometry (Haag-Streit, Bern, Switzerland); \(TMSa = \) TMS5 anterior surface (Tomey, Nagoya, Japan); \(TMSa = \) TMS5 anterior and posterior surface (Tomey); \(MAE = \) mean absolute error; \(MEE = \) median absolute error
another large patient series implanted with aspheric lenses based on Lenstar data and ray tracing.\textsuperscript{16}

Few studies describe the precision of cylindrical prediction. The magnitude of cylinder is important for the clinical result and quality of vision. However, simple subtraction of preoperative and postoperative cylinder powers will not differentiate overcorrection from undercorrection and does not do justice to the two-dimensional nature of the physical entity.

Some online calculators use a fixed and even wrong ratio between IOL plane and corneal plane power. A patient series of 3,046 eyes\textsuperscript{17} had a mean ratio of 0.74 ± 0.05 if Gaussian optics\textsuperscript{4} were applied. This is different from 0.68 used in some online calculators that will tend to overcorrect corneal astigmatism. These results are confirmed by others.\textsuperscript{18-20} The ratio varies considerably with spherical IOL power and vertex distance of the IOL.

Another reason for astigmatic overcorrection is the overestimation of total corneal astigmatism by just subtracting anterior radii. Dubbelman et al.\textsuperscript{21} found that posterior astigmatism compensates the anterior astigmatism by some 30% (0.3 D) in an average eye. A slight tendency to overcorrection can clearly be seen in our data when only keratometry was used.

The same authors calculated a composite index of 1.329 for a thin lens corneal model, similar to 1.327 derived from the Liou and Brennan model.\textsuperscript{22} Using the popular index 1.3375 will lead to further astigmatic overcorrection when Gaussian optics are applied. Ray tracing avoids problems associated with Gaussian optics and uses the measured geometry instead of assumptions.

In a previous study on higher power toric IOLs,\textsuperscript{1} we used the Haigis formula\textsuperscript{4} to calculate refraction for the steepest and flattest meridian of the cornea separately to predict a sphero-cylindrical residual refraction with a given toric IOL. We found a mean cylindrical prediction error as defined above of 0.97 D and the mean absolute difference between target induced

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Astigmatic correction of (A) 13 eyes with Alcon SN60TT (Alcon Laboratories, Inc., Fort Worth, TX); (B) 25 eyes with Alcon Toric IQ (Alcon Laboratories, Inc.); (C) 33 eyes with AMO Tecnis Toric (Abbott Medical Optics, Santa Ana, CA); and (D) 7 eyes with Carl Zeiss AT Torbi 709M (Carl Zeiss Meditec, Jena, Germany).}
\end{figure}
Figure 3. Astigmatic prediction error. (A) With the intended implantation axis the residual astigmatic power of each eye was calculated by ray tracing ("predicted astigmatism"). The vector difference between this prediction and the astigmatism of the manifest refraction is used as "cylindrical prediction error" (CPE). All calculations are based on Lenstar (Haag-Streit, Bern, Switzerland) corneal radii. (B) Same as A, but with TMS5 (Tomey, Nagoya, Japan) anterior radii instead of Lenstar radii. (C) Same as B, but with TMS5 anterior and posterior corneal surfaces (ie, taking into account the posterior corneal astigmatism). (D) Same as A, but with the average of Lenstar and TMS5 anterior and posterior astigmatism.
astigmatism\textsuperscript{10} and surgically induced astigmatism\textsuperscript{10} was 0.44 D. Alió et al.\textsuperscript{23} found 0.47 D and Visser et al.\textsuperscript{24} found 0.46 D using the same hardware (IOLMaster) and methodology. In our current series, the mean absolute difference was 0.26 to 0.30 D depending on the input data used.

Alió et al.\textsuperscript{25} described a difference vector in a case series of 27 eyes with a magnitude of 0.77 D at 1 month that can be directly compared to our results. We believe that the absolute value of the difference vector between achieved and predicted astigmatism (cylindrical prediction error) is best suited for describing achievable precision because it is directly comparable to spherical prediction error. Cylindrical prediction error was 0.51 D for the whole series and 0.43 D for the subgroup with distance corrected visual acuity of 1.0 or greater. Besides the different input data and ray tracing calculation, one reason for the higher predictive precision may again be the fact that predominantly toric aspheric lenses have been used. In our experience, aberration-correcting IOLs also improve spherical prediction error by approximately one-third.\textsuperscript{16} In this patient cohort, mean absolute error of spherical prediction error is at least 30\% lower than in similar studies to be found in the literature. The same is true for cylindrical prediction error.

In general, the posterior surface does play a significant role for total corneal astigmatism and should not be neglected when calculating toric IOLs.\textsuperscript{21,26,27}

Our clinical data suggest that keratometric input data are more stable (less outliers) than tomographic data, but tomography including the posterior curvature is potentially more precise, as can be seen by the lower median of cylindrical prediction error, especially in the high visual acuity group. For most patients, combined keratometry, Placido anterior curvature (topography), and Scheimpflug anterior and posterior curvature data (tomography) will deliver the best results. Anterior segment OCT might also be a useful tool for corneal tomography. Promising results regarding IOL calculation using such a device have been reported recently.\textsuperscript{28}

Interdevice agreement regarding cylinder axis was lower than expected in this patient group. The mean absolute difference between keratometric and topographic axis is 6\°, which is twice as high as our surgical alignment precision in this patient cohort (2.86\°) and that described previously.\textsuperscript{1} Therefore, the potential for improving surgical outcomes is higher in the field of preoperative measurement, planning, and computing.

Given the high predictive precision of toric IOL, any attempt to influence corneal astigmatism by incisional

### TABLE 2

Prediction Error of the Cylindrical Intraocular Lens Power (D)\textsuperscript{a}

<table>
<thead>
<tr>
<th>Visual Acuity by Group</th>
<th>No.</th>
<th>SD</th>
<th>Mean</th>
<th>Median</th>
<th>Min</th>
<th>Max</th>
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</thead>
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<tr>
<td>Lenstar cylinder</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All eyes</td>
<td>78</td>
<td>0.36</td>
<td>0.57</td>
<td>0.52</td>
<td>0.07</td>
<td>1.81</td>
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<tr>
<td>≥ 20/20</td>
<td>42</td>
<td>0.32</td>
<td>0.48</td>
<td>0.45</td>
<td>0.07</td>
<td>1.33</td>
</tr>
<tr>
<td>&lt; 20/20</td>
<td>36</td>
<td>0.39</td>
<td>0.69</td>
<td>0.70</td>
<td>0.10</td>
<td>1.81</td>
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<td>TMS5 anterior corneal cylinder</td>
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<td></td>
<td></td>
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<td>0.54</td>
<td>0.06</td>
<td>1.88</td>
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<tr>
<td>≥ 20/20</td>
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<td>0.46</td>
<td>0.42</td>
<td>0.06</td>
<td>0.95</td>
</tr>
<tr>
<td>&lt; 20/20</td>
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<td>0.48</td>
<td>0.69</td>
<td>0.63</td>
<td>0.09</td>
<td>1.88</td>
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<tr>
<td>TMS5 anterior/posterior cylinder</td>
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<td></td>
</tr>
<tr>
<td>All eyes</td>
<td>78</td>
<td>0.44</td>
<td>0.56</td>
<td>0.45</td>
<td>0.00</td>
<td>2.38</td>
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<tr>
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<td>1.26</td>
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<td>0.71</td>
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<td>2.38</td>
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<td></td>
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</tr>
<tr>
<td>All eyes</td>
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<td>0.38</td>
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<tr>
<td>&lt; 20/20</td>
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<td>0.61</td>
<td>0.51</td>
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<td>1.92</td>
</tr>
</tbody>
</table>

\(D = \) diopters; \(VA = \) visual acuity; \(SD = \) standard deviation

\(\textsuperscript{a}\)This figure is calculated as the absolute vector difference between manifest refractive cylinder and predicted cylinder based on different input data. In eyes with high distance corrected visual acuity, precision of refraction is much better and prediction error is significantly lower. Differences between intraocular lens groups are statistically significant (Friedman test, \(P < .05\)). The difference between visual acuity groups is also significant (Mann-Whitney U test, \(P < .01\)).

The Lenstar keratometry is manufactured by Haag-Streit, Bern, Switzerland, and the TMS5 topography is manufactured by Tomey, Nagoya, Japan.
techniques should be avoided because induced astigmatism is difficult to predict in an individual case. In non-symmetrical approaches such as standard-size steep-axis clear corneal incisions, coma, trefoil, and higher-order astigmatism will be induced that may spoil the preoperative calculations. We believe best results can be achieved by using a standardized aberration-neutral type of incision.

The ray tracing approach using combined keratometric and topographic data input in combination with toric aspheric lenses delivered the best predictive precision.

AUTHOR CONTRIBUTIONS
Study concept and design (PCH, P-RP); data collection (PCH); analysis and interpretation of data (PCH, WWH, P-RP, JW); drafting of the manuscript (PCH, P-RP); critical revision of the manuscript (WWH, JW); statistical expertise (P-RP); administrative, technical, or material support (P-RP)

REFERENCES
TABLE A
Properties of the Toric IOLs Used

<table>
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<tr>
<th>IOL</th>
<th>Material</th>
<th>Refractive Index</th>
<th>Cylinder @ IOL Plane</th>
<th>Shape</th>
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<td>1.55</td>
<td>Posterior 1.5 to 6.0 in 0.75</td>
<td>Spherical</td>
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<td></td>
<td>modified C</td>
<td></td>
<td>steps</td>
<td></td>
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<tr>
<td>Alcon Toric IQ</td>
<td>Hydrophobic acrylic single-piece</td>
<td>1.55</td>
<td>Posterior 1.5 to 6.0 in 0.75</td>
<td>Aspheric aberration correcting</td>
</tr>
<tr>
<td></td>
<td>modified C</td>
<td></td>
<td>steps</td>
<td></td>
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<tr>
<td>AMO Tecnis Toric</td>
<td>Hydrophobic acrylic single-piece</td>
<td>1.47</td>
<td>Posterior 1.0, 1.5, 2.25,</td>
<td>Aspheric aberration correcting</td>
</tr>
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<td></td>
<td>stepped C</td>
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<td>3.0, 4.0</td>
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<td>AT Torbi 709M</td>
<td>Hydrophilic acrylic single-piece</td>
<td>1.46</td>
<td>Anterior and posterior 2 to</td>
<td>Aspheric aberration correcting</td>
</tr>
<tr>
<td></td>
<td>mod. plate</td>
<td></td>
<td>12 in 0.5 steps</td>
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</tr>
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</table>

IOL = intraocular lens
The Alcon SN60TT and Alcon Toric IQ are manufactured by Alcon Laboratories, Inc., Fort Worth, TX; the AMO Tecnis Toric is manufactured by Abbott Medical Optics, Santa Ana, CA; and the AT Torbi 709M is manufactured by Carl Zeiss Meditec, Jena, Germany.

TABLE B
Prediction Error of the Spherical Equivalent Intraocular Lens Power

<table>
<thead>
<tr>
<th>Variable</th>
<th>No.</th>
<th>Mean</th>
<th>SD</th>
<th>MAE</th>
<th>MEE</th>
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<th>Min</th>
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<td>-1.05</td>
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<td>0.20</td>
<td>0.18</td>
<td>0.40</td>
<td>-0.91</td>
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<tr>
<td>All eyes</td>
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<td>0.36</td>
<td>0.27</td>
<td>0.23</td>
<td>0.80</td>
<td>-1.05</td>
</tr>
</tbody>
</table>

CDVA = corrected distance visual acuity; SD = standard deviation; MAE = mean absolute error; MEE = median absolute error

*The difference of the absolute prediction error between visual acuity groups is statistically significant (Mann-Whitney U test, P < .01). In eyes with high DCVA, precision of refraction is much better and therefore prediction error is much lower.

Figure A. Astigmatic correction in corneal plane. The astigmatic power of the implanted intraocular lenses is transformed to corneal plane taking into account the geometrical position as used in the ray tracing. This astigmatic power is shown as function of the absolute value of the preoperative astigmatism calculated from Lenstar (Haag-Streit, Bern, Switzerland) corneal radii.