62 Toric Calculations

Giacomo Savini and Adi Abulafia

Calculators for toric intraocular lenses (IOLs) have undergone a remarkable development over the last decade. Until around 2015, most calculators were directly developed by IOL manufacturers and suffered from two main limitations: (1) they were based on anterior keratometric values of corneal astigmatism, without taking posterior corneal astigmatism into account and (2) they assumed a fixed ratio between the cylinder of the IOL and the cylinder effect at the corneal plane (usually 1.46), based on the average pseudophakic eye [1].

Keratometric Astigmatism and Total Corneal Astigmatism

The clinical relevance of posterior corneal astigmatism (PCA) and its influence on total corneal astigmatism (TCA) was described by Ho et al. in 2009 and highlighted by Koch et al. in 2012 [2, 3]. These and other studies demonstrated that the posterior corneal surface has on average the steepest meridian vertically aligned and thus generates an against-the-rule (ATR) astigmatism [3–5]. As a consequence, if PCA is not accounted for, keratometric astigmatism (KA) usually overestimates TCA in eyes with with-the-rule (WTR) astigmatism and underestimates it in eyes with ATR astigmatism. For the same reason, studies comparing KA to TCA found the latter to predict more accurately the postoperative refractive astigmatism in eyes receiving toric and non-toric IOLs [6, 7]. Savini and Næser, for example, reported that using TCA leads to a mean prediction error (ERA, error in refractive astigmatism) close to zero, i.e., −0.13 ± 0.42 diopters (D) in eyes with WTR astigmatism and +0.07 ± 0.59 D in eyes with ATR astigmatism; on the contrary, using KA provided a mean overcorrection of the cylinder (−0.59 ± 0.34 D) in WTR eyes and a mean undercorrection (0.32 ± 0.42 D) in ATR eyes [6]. For surgeons who could not measure PCA and TCA, Koch et al. developed the first method used to predict TCA: the Baylor toric IOL nomogram. This took into account the mean values of PCA that they found (ATR astigmatism) and aimed to leave eyes after the toric IOL implantation with small amounts of WTR refractive astigmatism. It was required to manually perform the calculation following the guidelines indicated in some tables [8]. Shortly after the Barrett Toric Calculator was released, which was somehow revolutionary, it was the first to adjust the KA provided by keratometers included in the optical biometers in order to take PCA into

G. Savini (✉)
IRCCS Bietti Foundation, Rome, Italy

Studio Oculistico d'Azeglio, Bologna, Italy
e-mail: giacomo.savini@startmail.com

A. Abulafia
Department of Ophthalmology, Shaare Zedek Medical Center and the Hebrew University-Hadassah Medical School, Jerusalem, Israel

J. Aramberri et al. (eds.), *Intraocular Lens Calculations*, Essentials in Ophthalmology,
https://doi.org/10.1007/978-3-031-50666-6_62

account. Barrett Toric Calculator was followed by several calculators that shared the same purpose: optimize the KA and eliminate the fixed ratio between the cylinder at the IOL and at the corneal plane. Different studies have shown that toric calculators estimating TCA are more accurate than toric calculators using direct TCA measurements: the percentage of eyes with an absolute prediction error within 0.50 D increases from around 40% to around 60% [9, 10]. This apparently nonsense finding is likely to depend on the fact that estimating algorithms, in addition to posterior corneal astigmatism, take other sources of error into account (e.g., IOL tilt).

Solving the ACD Issue

Back in 2011, Goggin et al. pointed out that the Alcon web-based toric IOL calculator did not take into consideration the distance between the corneal and IOL planes when calculating the corneal plane cylinder equivalent power of the IOL [11]. They described an improved method to calculate the corneal plane cylinder equivalent power of the IOL by means of a thick lens vertex power formula, which contains the data of anterior chamber depth (ACD) and corneal pachymetry. However, different authors felt that his method had some limitations [12–14]. In order to take the ACD into account, we preferred to rely on the method previously described by Fam et al., who based their calculation on a thin-lens formula for IOL power calculation, the Holladay 1 formula [15]. Their method, known as meridional analysis, calculates the IOL power for the steep and flat meridians separately: the difference between the two values is the required IOL toricity for that eye, on condition that the postoperative ACD is separately calculated using the mean corneal power [16]. Using this method in a theoretical model, we found that the above mentioned ratio depends on the predicted ACD and can range from 1.29 in short eyes with shallow ACD to 1.86 in long eyes with deep ACD [17]. Today this issue has just a historical interest, since almost all calculators have fixed it.

The Influence of IOL Tilt

Both the natural crystalline lens and the IOL are known to be physiologically tilted towards the inferotemporal direction by a mean value of about 4–5° [18, 19]. This means that they are tilted horizontally around the vertical meridian with anterior displacement of the nasal portion. In a ray-tracing eye model, it has been shown that IOL tilting around the vertical meridian induces ATR astigmatism, which can be as high as 0.56 D with a 28.0 D IOL tilted 10° [20]. Consistently, Hirnschall et al. reported that IOL tilt is a relevant source of error in toric IOL calculation [21]. None of the currently available toric calculators enable direct input of IOL tilt, probably because optical biometers do not provide this value and it is difficult to develop a calculator including a parameter that is not readily available. However, the effect of tilt is indirectly taken into account by all toric calculators estimating TCA and this is one of the most likely reasons why such calculators are, on average, more accurate with respect to those using measured TCA values.

Current Toric Calculators

Abulafia-Koch Toric Calculator

This calculator uses the first published mathematical model that used a seperate regression formula for the X and Y vector components of anterior-based corneal astigmatism. This formula is aiming to compensate for the effect of posterior corneal astigmatism and any other physiological factors (e.g., IOL tilt) since it is derived from the differences between the postoperative anterior-based corneal astigmatism measurements and the calculated refractive astigmatism of the pseudophakic eye [22]. With minor andjusments from the original published formula, and the use of Fams' method to calculate the cylinder effect of a toric IOL at the corneal plane, it has been incorporated into several toric calculators such as the Hill-RBF, Hoya, Medicontur, Ophtec, Physiol, and Veracity surgical software. Its results are similar to those obtained with Barrett's calculator [22, 23].

Barrett Toric Calculator

Barrett's has been the first toric calculator (Figs. 62.1 and 62.2) to change the cylinder obtained as the keratometric astigmatism into a new value defined "net astigmatism". With respect to keratometric astigmatism, net astigmatism is lower in eyes with with-the-rule astigmatism and higher in eyes with against-the-rule astigmatism. The mathematics behind Barrett's calculator have never been published. However, it can be easily observed that net astigmatism also depends on the ACD and axial length values. Moreover, the version available on several biometry devices (e.g., IOLMaster700, Lenstar, etc.) and on the ASCRS (https://ascrs.org/tools/barrett-toric-calculator) and the APACRS website (https://calc.apacrs.org/toric_calculator20/Toric%20Calculator.aspx) does not only calculate the cylinder, but also the spherical equivalent power of the IOL.

Several papers have demonstrated that Barrett's toric calculator is one of the most accurate options to calculate the power of toric IOLs [24, 25]. Recently, 2 new features have been added to the online calculator.

1. An option to utilize direct measurements of the posterior cornea instead of using its standard mathematical model. This option incorporates an additional algorithem to compensate for the estimated effect of IOL tilt.
2. The K calculator which allows the user to select the keratometry measurements of up to three devices and provides integrated K values using vector-based calcultions.

Barrett True-K Toric Calculator

This toric calculator is designed for toric IOL power calculation for eyes following corneal ablation refractive surgery (myopic and hyperopic) and radial keratotomy. It is based on the Barrett True-K formula with an adjusted algorithm for toric IOL power calculation.

EVO 2.0 Toric Calculator

This unpublished toric calculator (Fig. 62.3), developed by Tun Kuan Yeo, MD, is available at the same website of the EVO 2.0 formula (https://www.evoiolcalculator.com/toric.aspx).

Fig. 62.1 Barrett toric calculator using predicted posterior corneal astigmatism reduces the keratometric astigmatism by the IOLMaster 700 (1.37 D @ 85°) to a net astigmatism of 0.78 D @ 82° (not shown), which is increased up to 0.97 D @ 83° after including SIA. Right: Barrett toric calculator using measured posterior corneal astigmatism reduces the keratometric astigmatism to a net astigmatism of 0.67 D @ 76° (not shown), which is increased up to 0.85 D @ 79° after including SIA

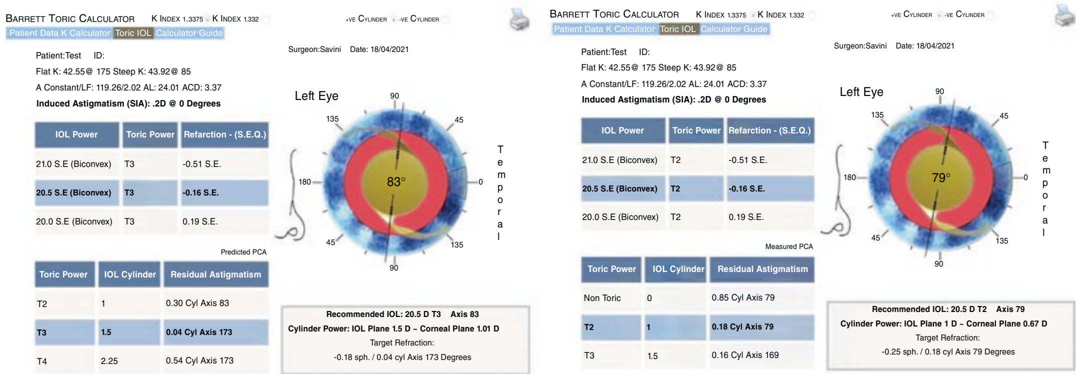

Fig. 62.2 Results of Barrett toric calculator with predicted posterior corneal astigmatism (left) and measured posterior corneal astigmatism (right). The predicted residual astigmatism with the implanted toric IOL (T3) is slightly different, as in the first case it is 0.04 D @ 173° and in the second case it is 0.16 D @ 169°

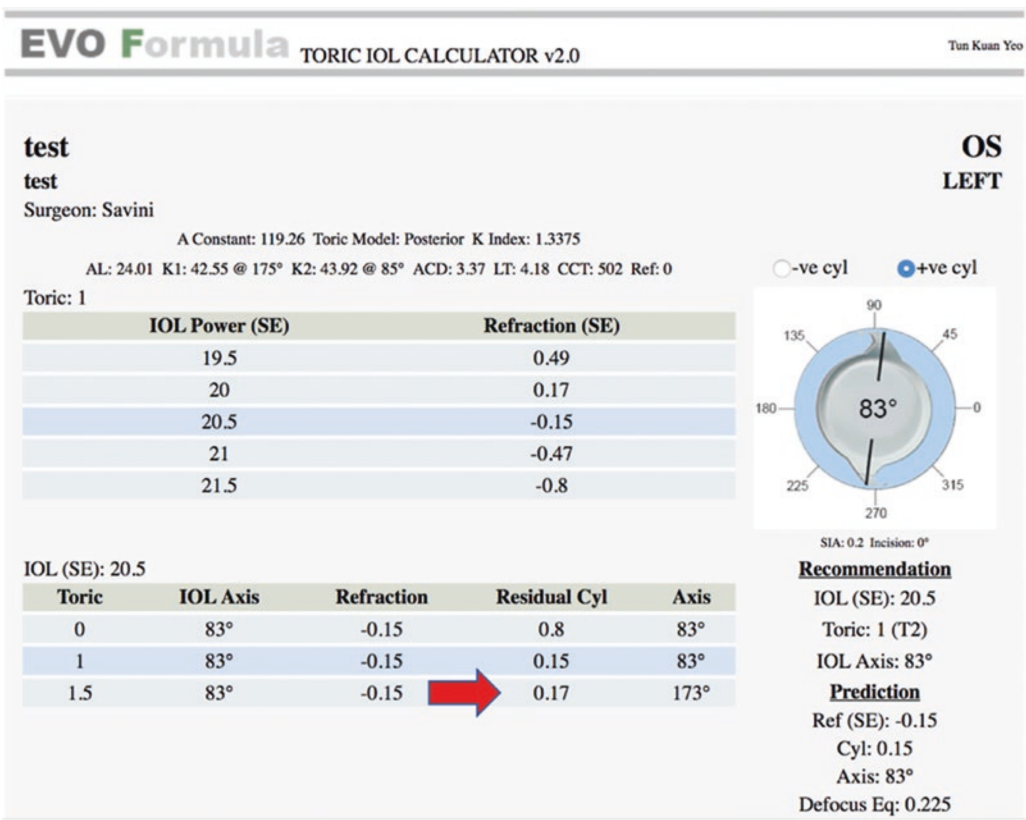

Fig. 62.3 EVO toric calculator directly provides the residual cylinder (0.17 D @ 173°)

The accuracy is close to that of the other toric calculators [26]. The online version provides the predicted SE based on the EVO 2.0 formula and has an additional feature for toric IOL power calculation for eyes following myopic corneal ablation refractive procedures.

Goggin Keratometry Adjustor Calculator

This calculator is different with respect to the other in this chapter, as it does not calculate the toric power of the IOL, but only adjusts the KA according to the coefficient published by Goggin et al. [27] The adjusted KA readings must be entered into a toric calculator that does not modify KA. Moreover, it is suggested that KA adjustments are unnecessary in eyes with KA > 2.0 D. The calculator is available at http://goggintoric.com.

Holladay Toric Calculator

This calculator has been released in 2019 following a publication by the author and is available at http://www.hicsoap.com/pro-description.php [28]. The Holladay toric calculator is based on the concept of the back-calculated SIA, which accounts for all factors that contribute to the difference between the preoperative K-reading and the ideal, back-calculated K-reading based on the actual postoperative refraction. The total SIA is calculated using the Gaussian vergence formula. It is worth mentioning that as opposed to other toric calculators, the corneal SIA is incorporated within the mathematical algorithem of this calculator and that it applies for surgeons who utilize temporal main corneal incisions (0/180°).

Johnson & Johnson Toric Calculator

Some manufacturers developed their own toric calculator. Johnson & Johnson uses a specific algorithm that can incorporate the effect of PCA, thus improving the refractive accuracy when compared to calculations based solely on KA [29]. The details of this PCA algorithm are unpublished, but it can be easily applied to any eye on the online toric calculator (https://tecnis-toriccalc.com) by selecting the option "Include Posterior Corneal Astigmatism".

Kane Toric Calculator

This calculator is available at https://www.iolformula.com (Fig. 62.4). Like for the Barrett and the EVO Toric Calculators, the Kane toric formula is unpublished. The author states that it "uses the Kane formula to calculate an ELP before using an advanced algorithm incorporating regression, theoretical optics, and artificial intelligence techniques to calculate the total corneal astigmatism". The results published by Kane et al. show the most accurate prediction with respect to the other calculators in this chapter [26]. The online version provide the SE prediction based on the Kane formula and it also has an option for toric IOL power calculation for eyes with keratoconus.

Næser-Savini Toric Calculator

The calculator developed by Drs. Kristian Næser and Giacomo Savini (Figs. 62.5 and 62.6) is based on the concept of optimized keratometry, a modification of the keratometric astigmatism that zeroes out the mean prediction, i.e., the difference between the predicted and the achieved refractive astigmatism [9]. Like for Barrett's calculator, also Næser-Savini toric calculator reduces the magnitude of the corneal astigmatism in eyes with a with-the-rule astigmatism and increases it in eyes with against-the-rule astigmatism. The new cylinder is calculated according to the following equation:

$$\text{Optimal keratometric astigmatism} = 0.103 + 0.836 \times \text{Measured keratometric astigmatism} + 0.457 \times \cos(2 \times \alpha).$$

This calculator takes ACD and axial length into consideration, according to meridional analysis as described by Fam [7]. It is available in its original version on the website of the Italian

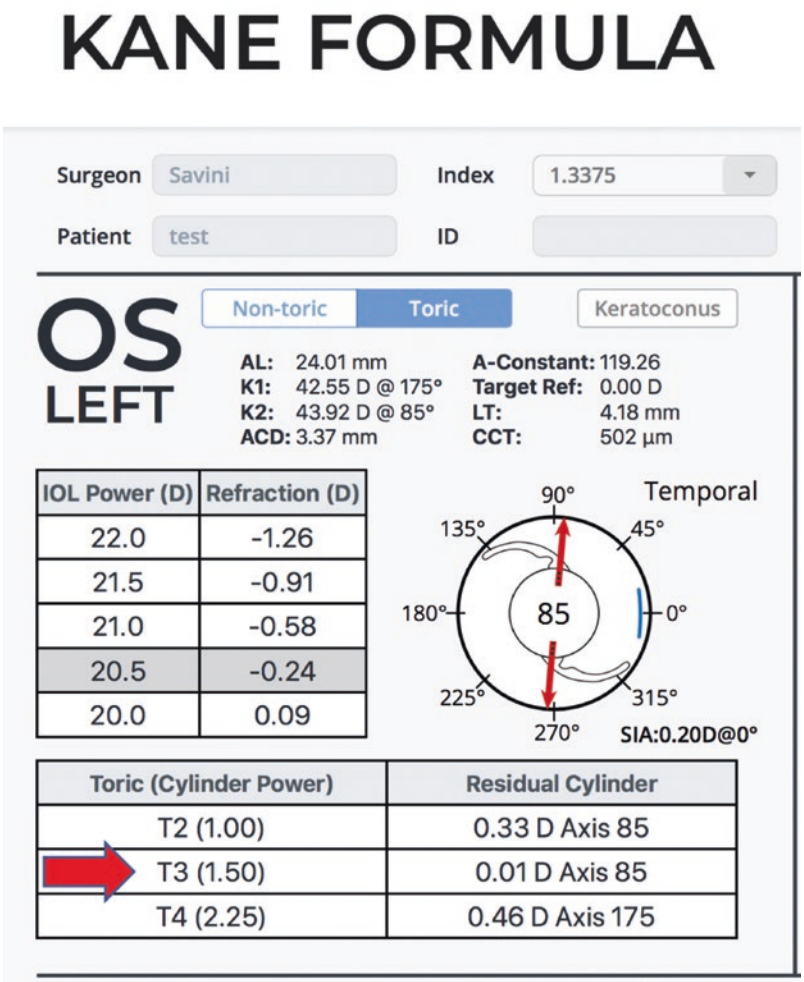

Fig. 62.4 Kane toric calculator directly provides the calculated toric IOL and the predicted residual cylinder (0.01 D @ 85°)

Ophthalmology Society (https://www.soiweb.com/toric-calculator/), where calculations are performed also with TCA by Scheimpflug cameras or anterior segment OCT for comparative purposes. The latest version is available on the Hoffer QST website (www.hofferqst.com). The published results are close to those obtained with the other calculators [9, 26].

Rayner Toric Calculator

Ray*trace* 3.5 is Rayner's proprietary online calculator for premium IOLs (available at, https://rayner.com/en/raytrace/). Ray*trace* 3.5 utilizes a combination of regression formulas, applying the recommended formula based on the patient's biometry input. PCA is an optional consideration, the mathematical method for which is unpublished.

Zeiss Toric Calculator

Calculations for Zeiss toric IOLs are performed by means of a proprietary online calculator (Z CALC 2.0, available at https://zcalc.meditec.zeiss.com) that offers two alternative options to include the PCA: (1) using Total Keratometry values directly measured by the IOLMaster 700

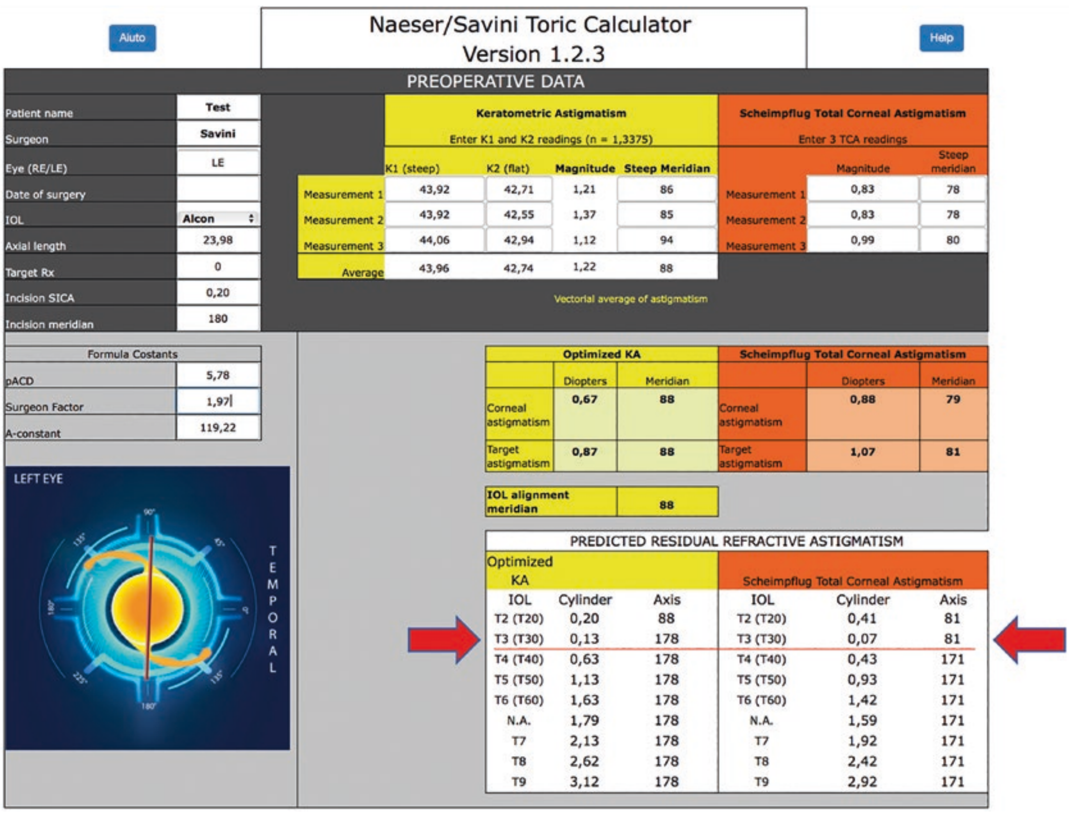

Fig. 62.5 Næser-Savini calculator (https://www.sedesoi.com/toric-2020/) suggests a T3/T30 Alcon IOL with both calculations. In the yellow section, the optimized keratometry, which takes posterior corneal astigmatism and IOL tilt into account, is derived from 3 keratometric measurements of corneal astigmatism: measurement 1 from Aladdin (Topcon), measurement 2 from IOLMaster 700 (Zeiss), and measurement 3 from OA-2000 (Tomey). The vectorial average of these three measurements is 1.22 D @ 88°. Optimization reduces corneal astigmatism to 0.67 D @ 88°. Addition of surgically induced corneal astigmatism (SICA) increases it up to 0.87 D @ 88°, which is the final target. In the orange section, three measurements of total corneal astigmatism by a Scheimpflug camera are entered: their vectorial average (0.88 D @ 79°) is lower than the mean non-optimized keratometric astigmatism (1.22 D @ 88°). Target astigmatism, including the effect of SICA, is 1.07 D @ 81°. The predicted residual refractive astigmatism is 0.13 D @ 178° with the optimized keratometric astigmatism and 0.07 D @ 81° with measured total corneal astigmatism

and (2) using an estimated TCA, which is based on measured KA and a mathematical model of PCA derived from clinical data (defined as Z CALC nomogram). The latter is recommended for post-refractive surgery eyes. So far, there are no studies showing which approach (Total Keratometry versus estimated TCA) is more accurate. On the other hand, Z CALC 2.0 with estimated TCA has been shown to be more accurate with respect to the previous version of the same calculator [30].

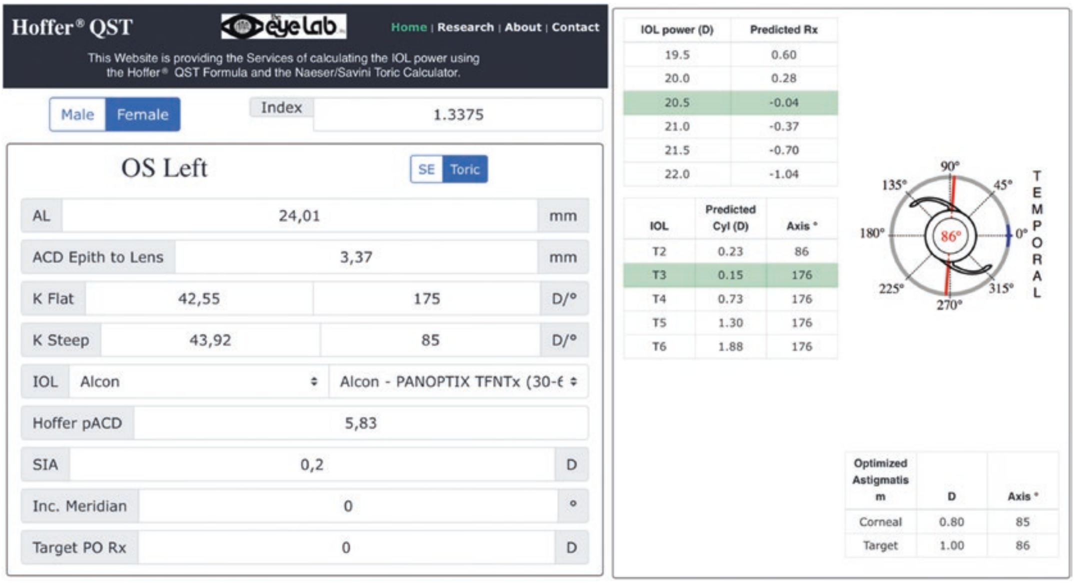

Fig. 62.6 The Næser-Savini calculator version available on the website of the Hoffer QST formula (https://hoffer-qst.com) reduces the keratometric astigmatism by the IOLMaster 700 (1.37 D @ 85°) to an optimized value of 0.80 D @ 85°, which is increased up to 1.00 D @ 86° after including the surgically induced astigmatism. The predicted cylinder with the T3 IOL is 0.15 D @ 176°

Results

Refractive results of toric calculators have remarkably improved over the last decade, although they are still far from perfection, as some amount or residual refractive astigmatism is often observed. Like for calculation of non-toric IOLs, the main outcome is the prediction error, which—in the case of toric IOLs—is the difference between the postoperative refractive astigmatism and the predicted refractive astigmatism. This analysis should consider the actual orientation of the toric IOL, evaluated at the slit lamp under pupil dilation, and not just the planned orientation.

When analyzing such results, we should look at two main outcomes: the centroid prediction error and the percentage of eyes with an absolute prediction error within 0.50 D. The former is the vectorial average of all prediction errors and provides us with an estimation of the systematic deviation from the predicted refractive astigmatism, so that values closer to zero reveal a better performance of a given calculator; its standard deviation is a measure of the spread of the results. The latter is a useful metric to understand what we can expect, from a clinical point of view, in our patients, as it explains in how many cases we are able to reach an absolute prediction error within 0.50 D, which can be arbitrarily selected as a very good result.

All current calculators lead to a mean centroid prediction error close to zero (Table 62.1) [9, 10, 22, 26]. On the contrary, older calculators based on standard keratometric values (with no optimization to take the PCA into consideration) lead to a systematic overcorrection in eyes with WTR astigmatism and undercorrection in eyes with ATR astigmatism [9, 22]. Calculators based on TCA measurements, such as those provided by Scheimpflug cameras, usually provide intermediate outcomes, as they are better than those based on KA and—on average—are less accurate than those estimating TCA [9, 10, 25].

The percentage of eyes with an absolute prediction error within 0.50 D ranges between 55 and 79% with calculators estimating TCA,

Table 62.1 Refractive outcomes obtained with current toric calculators

	Centroid Prediction Error (D @ angle) + standard deviation	Percentage of eyes with an absolute prediction within 0.50 D
Abulafia-Koch [10]	0.07 ± 0.26 @ 172°	72.0%
Abulafia-Koch [26]	0.11 ± 0.65 @ 110°	59.5%
Abulafia-Koch [9]	0.17 ± 0.77 @ 70°	54.7%
Abulafia-Koch [22]	0.04 ± 0.31 @ 176°	78.2%
Barrett [10]	0.13 ± 0.37 @ 174°	67.0%
Barrett [26]	0.10 ± 0.64 @ 111°	59.9%
Barrett [9]	0.11 ± 0.63 @ 56°	57.2%
Barrett [22]	0.05 ± 0.30 @ 176°	79.5%
EVO 2.0 [26]	0.16 ± 0.63 @ 100°	58.9%
Holladay [26]	0.13 ± 0.66 @ 168°	53.9%
Johnson & Johnson [29]	0.19 ± 0.41 @ 3°	53.0%
Kane [26]	0.03 ± 0.60 @ 163°	65.6%
Næser-Savini [9]	0.11 ± 0.61 @ 47°	57.8%
Næser-Savini [26]	0.01 ± 0.67 @ 150°	56.7%

whereas it is close to 40% with calculators using measured TCA and around 25–30% with calculators using KA [9, 10, 22, 25, 26].

Example of the results obtained from different toric calculators in a patient with WTR astigmatism who ended up with plano refraction after implantation of toric 20.5 D Panoptix TFNT30 oriented at 88°.

References

1. Savini G, Hoffer KJ, Ducoli P. A new slant on toric intraocular lenses power calculation. J Refract Surg. 2013;29:348–54.
2. Ho JD, Tsai CY, Liou SW. Accuracy of corneal astigmatism estimation by neglecting the posterior corneal surface measurement. Am J Ophthalmol. 2009;147:788–95.
3. Koch DD, Ali SF, Weikert MP, et al. Contribution of posterior corneal astigmatism to total corneal astigmatism. J Cataract Refract Surg. 2012;38:2020–87.
4. Tonn B, Klaproth OK, Kohnen T. Anterior surface-based keratometry compared with Scheimpflug tomography-based total corneal astigmatism. Invest Ophthalmol Vis Sci. 2015;56:291–8.
5. Savini G, Versaci F, Vestri G, Ducoli P, Næser K. Influence of posterior corneal astigmatism on total corneal astigmatism in eyes with moderate to high astigmatism. J Cataract Refract Surg. 2014;40:1645–53.
6. Savini G, Næser K. An analysis of the factors influencing the residual refractive astigmatism after cataract surgery with toric intraocular lenses. Invest Ophthalmol Vis Sci. 2015;56:827–35.
7. Klijn S, Reus NJ, Van Der Sommen CM, et al. Accuracy of total corneal astigmatism measurements with a Scheimpflug imager and a color light-emitted diode corneal topographer. Am J Ophthalmol. 2016;167:72–8.
8. Koch DD, Jenkins RB, Weikert MP, et al. Correcting astigmatism with toric intraocular lenses: effect of posterior corneal astigmatism. J Cataract Refract Surg. 2013;39:1803–9.
9. Savini G, Næser K, Schiano-Lomoriello D, Ducoli P. Optimized keratometry and total corneal astigmatism for toric intraocular lens calculation. J Cataract Refract Surg. 2017;43:1140–8.
10. Ferreira TB, Ribeiro P, Ribeiro FJ, OO'Neill JG. Comparison of methodologies using estimated or measured values of total corneal astigmatism for toric intraocular lens power calculation. J Refract Surg. 2017;33:794–800.
11. Goggin M, Moore S, Easterman A. Outcome of toric intraocular lens implantation after adjusting for anterior chamber depth and intraocular lens sphere equivalent power effects. Arch Ophthalmol. 2011;129:998–1003.
12. Simpson MJ. Refractive outcomes for toric intraocular lenses. Arch Ophthalmol. 2012;130:945–6.
13. Holladay JT. Exact toric intraocular lens calculations using currently available lens constants. Arch Ophthalmol. 2012;130:946–7.
14. Savini G, Hoffer KJ. Toric intraocular lens calculations. Arch Ophthalmol. 2012;130:947–8.
15. Holladay JT, Prager TC, Chandler TY, et al. A three-part system for refining intraocular lens power calculations. J Cataract Refract Surg. 1988;14:17–24.
16. Fam HB, Lim KL. Meridional analysis for calculating the expected spherocylindrical refraction in eyes with toric intraocular lenses. J Cataract Refract Surg. 2007;33:2072–6.
17. Savini G, Hoffer KJ, Carbonelli M, Ducoli P, Barboni P. Influence of axial length and corneal power on the astigmatic power of toric intraocular lenses. J Cataract Refract Surg. 2013;39:1900–3.
18. Kimura S, Morizane Y, Shiode Y, Hirano M, Doi S, Toshima S, Fuijiwara A, Shiraga F. Assessment of tilt and decentration of crystalline lens and intraocular

lens relative to the topographic axis using anterior segment optical coherence tomography. PlosOne. 2017;12(9):e01184066.
19. Wang L, Guimaraes de Souza R, Weikert MP, Koch DD. Evaluation of crystalline lens and intraocular lens tilt using a swept-source optical coherence tomography biometer. J Cataract Refract Surg. 2019;45:35–40.
20. Weikert MP, Golla A, Wang L. Astigmatism induced by intraocular lens tilt evaluated via ray tracing. J Cataract Refract Surg. 2018;44:745–9.
21. Hirnschall N, Findl O, Bayer N, Leisser C, Norrby S, Zimper E, Hoffmann P. Sources of error in toric intraocular lens power calculation. J Refract Surg. 2020;36:646–52.
22. Abulafia A, Koch DD, Wang L, Hill WE, Assia EI, Franchina M, Barrett GD. New regression formula for toric intraocular lens calculations. J Cataract Refract Surg. 2016;42:663–71.
23. Ribeiro FJ, Ferreira TB, Relha C, Esteves C, Gaspar S. Predictability of different calculators in the minimization of postoperative astigmatism after implantation of a toric intraocular lens. Clin Ophthalmol. 2019;13:1649–56.
24. Reitblat O, Levy A, Kleinmann G, Abulafia A, Assia EI. Effect of posterior corneal astigmatism on power calculation and alignment of toric intraocular lenses: comparison of methodologies. J Cataract Refract Surg. 2016;42:217–25.
25. Abulafia A, Hill WE, Franchina M, Barrett GD. Comparison of methods to predict residual astigmatism after intraocular lens implantation. J Refract Surg. 2015;31:699–707.
26. Kane JX, Connell B. A comparison of the accuracy of 6 modern toric intraocular lenses formulas. Ophthalmology. 2020;127:1472–86.
27. Goggin M, Zamora-Alejo K, Easterman A, van Zyl L. Adjustment of anterior corneal astigmatism values to incorporate the likely effect of posterior corneal curvature for toric intraocular lens calculation. J Refract Surg. 2015;31:98–102.
28. Holladay JT, Pettit G. Improving toric intraocular lens calculations using total surgically induced astigmatism for a 2.5 mm temporal incision. J Cataract Refract Surg. 2019;45:272–83.
29. Canovas C, Alarcon A, Rosén R, Kasthurirangan S, Ma JK, Koch DD, Piers P. New algorithm for toric intraocular lens power calculation considering the posterior corneal astigmatism. J Cataract Refract Surg. 2018;44:168–74.
30. Lesieur G. Microincision cataract surgery with implantation of a bitoric intraocular lens using an enhanced program for intraocular lens power calculation. Eur J Ophthalmol. 2020;30:1308–13.