Coma Influence on Manifest Astigmatism in Coma-Dominant Irregular Corneal Optics

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ABSTRACT

PURPOSE: To evaluate the influence of coma on manifest refractive cylinder (MRC) in eyes with coma-dominated corneal optics and suggest alternative guidelines for surgical planning of astigmatism correction in topography-guided ablation and toric intraocular lens (IOL) exchange surgery.

METHODS: Twelve eyes with coma-dominant corneal optics and low lenticular astigmatism were selected. The astigmatism remaining after subtraction of total corneal astigmatism (TCA) and lenticular astigmatism from MRC, termed discrepant astigmatism, was calculated and correlated to corneal coma at the anterior surface. Refractive and topography data were then used to simulate topography-guided refractive surgery (topography-guided group) in 7 eyes and lenticular exchange surgery with toric intraocular lens (IOL) implantation (toric IOL group) in 5 eyes. The estimated postoperative MRC after correction of TCA or MRC for each group was compared.

RESULTS: The axis and amplitude of discrepant astigmatism correlated strongly with the axis and amplitude of coma. In the topography-guided group, where topography-guided ablation eliminated corneal higher order aberrations (HOAs), TCA-based correction led to less estimated postoperative manifest astigmatism than MRC-based correction. In the toric IOL group, where removal of the crystalline lens did not affect corneal HOAs, MRC-based correction via toric IOL implantation led to less estimated postoperative astigmatism than TCA-based correction.

CONCLUSIONS: Discrepant astigmatism in eyes with coma-dominant corneal optics correlates with coma. In such eyes, treating TCA, along with corneal HOAs, instead of MRC, seems appropriate in topography-guided treatments, whereas treating MRC may be a better choice in lenticular exchange surgery with toric IOL implantation, where corneal HOAs are not treated.

Non-rotationally symmetric corneal higher order aberrations (HOAs), commonly expressed as coma or coma-like HOAs, appear with tilted or decentered incident wavefront with respect to the corneal optical surface. Any corneal pathology that leads to orthogonally asymmetric morphology, such as keratoconus,[1,2] corneal ectasia after laser in situ keratomileusis (LASIK),[3] decentered laser refractive[4] and incisional corneal surgery, pterygium surgery,[5] and corneal scarring due to injuries or keratitis, most often results in coma-dominant HOAs. In these conditions, visual distortions and decreased visual acuity occur irrespective of spherocylindrical error and its correction.[6,7]

The presence of HOAs has an influence on the subjective manifest refraction and the manifest refractive cylinder (MRC) in particular. MRC is composed of anterior corneal astigmatism, posterior corneal astigmatism, lenticular astigmatism, possible influence from the retina, and neural processing. In 1997, Alpins[8] described the difference between anterior corneal topographic astigmatism and MRC as "ocular residual astigmatism," with the crystalline lens being normally the source of ocular residual astigmatism along with the posterior corneal astigmatism. Because the latter represents an important component of the corneal optics,[9,10] ray-traced total corneal astigmatism (TCA), comprising the astigmatic effect of both the anterior and posterior cornea, has been used in the current study instead of anterior corneal astigmatism.

In an eye with significant HOAs, manifest refraction is limited to find a best correction only using lower order aberrations (sphere and cylinder). Therefore, MRC measurement will be influenced by the perception of coma and coma-like HOAs as astigmatism.[11,12] In other words, a cylinder lens provides some visual benefit and is therefore accepted by the patient as a partial correction of the coma. The coma-derived manifest astigmatic component causes a discrepancy between the MRC and the sum of the TCA and lenticular astigmatism. We have previously described this discrepancy and referred to this as the discrepant astigmatism.[13] Therefore, the selection of the astigmatism component to be corrected when treating eyes with irregular corneal optics warrants special attention in both topography-guided refractive surgery and in lenticular exchange surgery with toric intraocular lens (IOL) implantation.

The current study emphasizes the use of an analytical approach in estimating the origin and relationships between various components of ocular astigmatism in eyes with coma-dominated corneal optics and proposes guidelines for astigmatism correction when such eyes are treated by topography-guided refractive surgery or by lenticular exchange surgery with toric IOL implantation. Table A (available in the online version of this article) contains a list of abbreviations for various astigmatic components used in this study.

PATIENTS AND METHODS

Among patients referred for therapeutic refractive surgery or cataract surgery at the Eye Department of the University Hospital of Northern Norway between January 2015 and January 2017, 12 eyes of 12 patients with coma-dominant corneal optics due to keratoconus (10 eyes), post-LASIK diffuse lamellar keratitis (1 eye), and post-photorefractive keratectomy haze (1 eye) were selected for the astigmatism correction simulation. Among the 12 patients, 7 patients aged younger than 30 years were selected for topography-guided corneal refractive surgery simulation (topography-guided group) and 5 patients older than 55 years who had signs of cataract were selected for simulation of lenticular exchange surgery with toric IOL implantation (toric IOL group). The inclusion criteria were: (1) anterior corneal topography with orthogonally asymmetric power along any meridian exceeding 2.00 diopters (D) and/or axis misalignment between principal hemi-meridians greater than 10°; (2) vector difference between TCA and MRC of 1.50 D or greater; and (3) the estimated amount of lenticular astigmatism lower than the calculated discrepant astigmatism (Table 1). The exclusion criteria were oblique TCA, MRC, and coma, because the complexity of calculations for such cases was beyond the scope of this study.

Astigmatism and Coma Measurements

Corneal topography/tomography and aberrometry were acquired using a Scheimpflug-based tomographer (Precisio; iVIS Technology) and Placido topographer/aberrometer (OPD-Scan II; NIDEK). TCA was calculated by the Precisio, using ray-tracing. Estimation of lenticular astigmatism was based on the vectorial difference between internal astigmatism (IA), measured by the OPD-Scan II, and posterior corneal astigmatism (PCA), measured by the Precisio. MRC was obtained from non-cycloplegic manifest refraction. MRC was first converted to cross-cylinder notation, and then transferred from the spectacle plane to the corneal plane using the vertex distance of 12 mm for direct comparison with the corneal astigmatism. Discrepant astigmatism was calculated as the difference between MRC and the vectorial sum of TCA and lenticular astigmatism. The orientation of astigmatism is presented as the axis of corrective cylinder (using negative cylinder values). The measurement instruments and calculation methods for the different components of astigmatism and the respective abbreviations are listed in Table A.

The magnitude of the anterior corneal coma was defined as the square root of the sum of C^{1}_{3} and C^{-1}_{3} measured by the OPD-Scan II aberrometer within a 3.5-mm zone, the same zone at which the keratometry values were obtained. The coma axis was defined as the axis passing through both the corneal vertex and the center of the specific elevated area representing the morphological substrate of coma on the anterior corneal elevation topography, using toric fitting, as shown in the example in Figure 1. Coma with axis oriented at 90° ± 30° was defined as vertical coma; coma with axis oriented at 180° ± 30° was defined as horizontal coma. Coma with other orientations was defined as oblique coma. The axes of discrepant astigmatism and anterior corneal coma were directly compared. The relationship between magnitude of discrepant astigmatism and coma was evaluated by Spearman correlation, using SPSS software version 13.0. (IBM Corporation).

Simulations

In the topography-guided group, imported data from the Precisio were used as the basis for a customized ablation design by Corneal Interactive Programmed Topographic Ablation software (LIGI), which generates estimated postoperative topography by point-by-point subtraction of the ablation plan data from the preoperative anterior elevation topography. The simulations comprised corneal vertex fitting using two different toric surfaces, defined as the targeted surfaces for the two strategies aiming for two different astigmatism corrections. Strategy 1 aimed to correct TCA and the anterior corneal surface irregularities (the source of anterior corneal HOAs). Strategy 2 aimed to correct MRC and the anterior corneal surface irregularities. In both cases, ablation consisted of the tissue between the existing anterior corneal surface and the targeted regular surface within a 6-mm optical zone (Figure A, available in the online version of this article).

In the toric IOL group, simulated removal of the crystalline lens, performed without treatment of the anterior corneal irregularities, led to elimination of the lenticular astigmatism, whereas the effect of the induced corneal astigmatism due to surgical incisions was not considered. Strategies 1 and 2 were simulated by choice of toric IOL astigmatic power for correction of TCA and MRC, respectively.

The estimated postoperative MRC was calculated and compared using the two strategies for the topography-guided and toric IOL groups. The influence of the manifest sphere and spherical aberration was not analyzed, nor were the possible influence from the retina and neural processing, because they were outside the scope of the study.

The regional ethics committee granted exemption from approval. The study obtained approval from the Norwegian Data Protection Authority.

RESULTS

All eyes had (up to sixth order) root mean square HOAs greater than 0.3 µm at the 3.5-mm diameter, with coma as the dominant aberration (Table 1). All patients had decreased corrected distance visual acuity and/or visual disturbances not correctable by sphere and cylinder. Table 1 also shows the patients' astigmatism, including the MRC, objectively measured astigmatism components, and coma for each eye. The mean absolute difference in axis between discrepant astigmatism and coma was 11.3 ± 6.81 degrees (range: 2 to 22 degrees), whereas the magnitude of discrepant astigmatism was positively correlated with magnitude of anterior corneal coma ($P = .026$; $R = 0.64$; $R^2 = 0.41$), as shown in Figure 2.

Table 2 shows the estimated postoperative MRC for the two strategies simulated in the two groups. In the topography-guided group, strategy 1 corrected anterior corneal HOAs along with TCA, resulting in a spherical cornea (ie, no corneal astigmatism remaining), leaving lenticular astigmatism as the only astigmatism component. Strategy 2 corrected anterior corneal HOAs along with MRC, resulting in induction of corneal astigmatism equal to the inverse discrepant astigmatism, due to its double treatment; First by topography-guided ablation, regularizing the anterior corneal surface and treating the coma itself, and second by correction of MRC, which included the pseudo-astigmatism caused by the presence of coma. Because all of the cases in the study had coma-dominant optics, with lenticular astigmatism lower than discrepant astigmatism, strategy 2 resulted in significantly higher estimated postoperative MRC. Figure A shows the estimated postoperative anterior corneal topography after both strategies for all 7 cases in the topography-guided group.

In the toric IOL group, strategy 1 was to choose the toric IOL power and axis based on the TCA (Figure BD, available in the online version of this article). Using this strategy, TCA was neutralized by the toric IOL and lenticular astigmatism was eliminated by extraction of the crystalline lens, leaving uncorrected astigmatic refractive effect of the coma as the source of estimated postoperative MRC. In strategy 2 in this group, the toric IOL power and axis were based on MRC (Figure BE). This neutralized the astigmatic refractive effect of the coma and TCA, but it also contained the lenticular astigmatism component, which was effectively corrected twice, after removal of the crystalline lens. This resulted in rest astigmatism inverse to lenticular astigmatism as the estimated postoperative MRC. Because all cases in the study had coma-dominant optics and lenticular astigmatism lower than discrepant astigmatism, strategy 2 in which the toric IOL corrected for the influence from coma resulted in lower estimated postoperative MRC than strategy 1.

DISCUSSION

This study investigated the influence of coma on manifest refractive cylinder in eyes with coma-dominated corneal optics and evaluated its therapeutic consequences. We found a positive correlation between the amount and orientation of coma and the remaining astigmatism after subtraction of the TCA and lenticular astigmatism from the MRC. This led to the conclusion that treating TCA in eyes with high coma is preferred to treating manifest cylinder if topography-guided ablation is used, although treatment of manifest cylinder may be a better option in lenticular exchange surgery with the toric IOL, where corneal coma is not treated. Both of these conclusions differ from the standard approach to treating astigmatism in virgin eyes.

Manifest refraction, a common means of assessing the manifest sphere, astigmatism, and visual acuity, is influenced by the amount, type, and spatial distribution of corneal HOAs. It has been shown that depending on the refraction technique, positive or negative spherical aberrations may induce spherical hyperopic or myopic errors, respectively.[14] Similarly, ocular coma may cause manifest refraction to add astigmatism because the patient's retinal image coma component may be partially improved by cylinder.[11-13] During phoropter testing, the resultant manifestly refracted cylinder power and axis will be some sort of vectorial sum of (at least) two components: one caused by "pure" OA (in the sense of second-order aberration with ± 2 as frequency), and the other caused by coma and other odd-order HOAs manifestly refracting as cylinder (Figure BA). Another challenge is that obtaining a reliable manifest refraction in eyes with significant coma is difficult and less repeatable. There can be more than one endpoint for both magnitude and axis of astigmatism, one where the point spread function is optimized in one axis and another where the point spread function is optimized in another axis.

Our results showed a significant association between discrepant astigmatism and coma, in terms of good consistency in their axes and positive correlation in their magnitude. Hence, we concluded that coma seems to be a significant source of error producing the discrepancy between the MRC and ocular astigmatism. Table 2 shows the influence of coma with-the-rule and against-the-rule on the MRC. The findings confirm our previous suggestion[13] that vertical coma influences MRC by cancelling the effect of with-the-rule and increasing the effect of against-the-rule ocular astigmatism, whereas horizontal coma enhances the effect of with-the-rule ocular astigmatism and cancels the effect of against-the-rule ocular astigmatism.

Surgical vision correction in visually disturbing corneal pathology has been increasingly used in the form of topography-guided excimer laser ablation[15,16] or toric IOL implantation[17] in stable corneas, or in combination with corneal cross-linking in unstable corneas.[18] Topography-guided custom ablation in virgin eyes has also become more prevalent[19,20] and the issue of deciding between corneal and MRC treatment has been actualized for that purpose. The term "topography modified refraction" has also been coined for addressing this issue,[21] suggesting that the combination of refractive and corneal data provides better outcomes than treatment by MRC, leaning toward the use of the anterior corneal astigmatism in case of discrepancy. However, Wallerstein et al[22] concluded that clinically significant sources of astigmatism such as posterior corneal astigmatism, lenticular astigmatism, and cortical perception tend to lead to outcome inaccuracies when anterior corneal astigmatism was used as the astigmatism treatment endpoint in a clinical study in 1,274 treated eyes. It is also important to note that most virgin eyes in which it is proposed that topography-guided custom ablation could be beneficial involve corneas with inferior steepening on topography (ie, coma), so it is important to ensure that this inferior steepening is not a result of a mild keratoconus by epithelial thickness profile mapping.[23-26] Excluding keratoconus by epithelial profiles has been shown to be effective in allowing LASIK to be performed despite increased coma and inferior steepening.[27]

When a significant discrepancy between TCA and MRC is discovered, a comprehensive analysis of the origin of the discrepancy is critical in planning any refractive treatment. In eyes with normal corneas, lenticular astigmatism is usually considered to be the main reason for the discrepancy, and ordinary elective corneal refractive surgery planned with sphere and cylinder correction as measured by manifest refraction leads to good postoperative visual outcomes in most cases.[22] In lenticular exchange surgery with toric IOL, MRC is neglected and (anterior) corneal astigmatism is typically corrected.[28] However, these may not be applicable in cases with irregular corneal optics if the coma component is higher than the lenticular astigmatic component. A suggestion for correction of astigmatism in topography-guided ablation and lenticular exchange surgery with toric IOL in corneas with coma-dominant irregular optics is shown in Figure 3, where either MRC or TCA are used as endpoints.

Why might topography-guided refractive surgery, where corneal HOAs are treated together with TCA instead of MRC, be preferable in eyes with coma-dominant corneal optics and low lenticular astigmatism? In the presence of coma-like HOAs, MRC represents a vectorial sum of TCA, lenticular astigmatism, and HOAs manifestly refracting as astigmatism (Figure BA). When corneal HOAs and TCA are both treated by topography-guided ablation, all sources of MRC, except for lenticular astigmatism, are addressed (Figure BB). However, when corneal HOAs and MRC are treated, then the corneal coma itself, as a part of the treated corneal HOAs, and its effect on MRC (ie, discrepant astigmatism) are both being treated. This amounts to "double treatment" of discrepant astigmatism (ie, removal of the cause and simultaneous treatment of its effect) (Figure BC). Hence, in the topography-guided group, strategy 1 (treatment of TCA and HOAs) led to regularized corneal optics with no HOAs and no remaining TCA, with lenticular astigmatism as the only source of estimated postoperative MRC. In contrast, strategy 2 (treating MRC and HOAs) resulted in significant estimated postoperative MRC due to the effect of the double treatment of discrepant astigmatism (Table 3). The simulation did not compensate for the epithelial remodeling to compensate for the postoperative change in stromal surface,[29-31] assuming that the design of the transition zone would result in even epithelial thickness postoperatively.

Why might selection of toric IOL based on MRC instead of TCA be preferable in lens exchange surgery in eyes with coma-dominant corneal optics and low lenticular astigmatism? Lens exchange surgery eliminates lenticular astigmatism, with the removal of the crystalline lens, so the TCA along with the astigmatic effect from coma-like HOAs should be corrected. If the TCA is corrected by toric IOL, the corneal HOAs would be the remaining source of estimated postoperative MRC (Figure BD). On the other hand, if MRC is used as the basis for the selection of toric IOL, then the TCA plus the astigmatic contribution of coma-like HOAs would be accounted for. However, that would also amount to double correction of lenticular astigmatism because it would be removed along with the crystalline lens (Figure BE). In our cases, lenticular astigmatism was of lower magnitude than discrepant astigmatism, and the estimated postoperative MRC with strategy 2 (where MRC was treated by toric IOL) was lower than that with strategy 1 (where TCA was treated by toric IOL) (Table 2).

In this study, we analyzed cases with coma-dominant corneal optics with a difference between MRC and TCA of 1.50 D or greater and with relatively insignificant lenticular astigmatism. Only cases with discrepant astigmatism greater than lenticular astigmatism were analyzed to minimize the relative influence of the lenticular astigmatism and to better focus on the influence of coma. This obviously implies that our conclusions must be strictly limited to the eyes with discrepant astigmatism greater than lenticular astigmatism. In therapeutic corneal refractive surgery, where spectacle independence is not the primary goal, untreated lenticular astigmatism may be a lesser issue. Hence, using the outlined strategy with TCA as the astigmatism treatment endpoint in therapeutic topography-guided treatments should most likely be acceptable. However, if the intention is also to correct lenticular astigmatism, a precise and reliable measurement of the lenticular astigmatism is necessary, and lenticular astigmatism along with TCA should be used to calculate the cylinder correction by vector analysis. Alternatively, aberrometry providing reliable measurement of pure ocular astigmatism may be used. In his vector planning approach, Alpins[8] and Alpins and Stamatelatos[32] suggested a 60%/40% division between the MRC and the anterior corneal astigmatism, whereas Gatinel et al[33] reported measurement of ocular astigmatism without interaction from HOAs, using a novel polynomial decomposition method. With the latter technology, topography-guided corneal ablation targeting correction of ocular astigmatism could be a solution for aberrated cornea, where all of the astigmatic components would be addressed.

In the current study, we assessed the lenticular astigmatism by combining two different instruments using three different technologies (Scheimpflug- and Placido-based topography and optical path difference-based wavefront aberrometry). In addition to the registration error that may occur between any two separate examinations, the potential error due to data interchangeability/compatibility between the instruments should also be considered. Unfortunately, technology for direct measurement of lenticular astigmatism with a single instrument is not available yet, and the astigmatic power of the lens has only been measured precisely in vitro.[34] Solid clinical research in this respect, especially on the compensatory dynamics of lenticular astigmatism, is lacking. Information in that respect would be invaluable for planning topography-guided laser ablation with TCA neutralization. Current, hybrid, corneal spectral-domain optical coherence tomography/ Placido topography device (MS-39; CSO) combined with their high-resolution pyramidal aberrometry (Osiris; CSO) may, for the first time, give us reliable measurements of the lenticular astigmatism, along with the TCA. Still, for keratoconic eyes, an ablative procedure would be performed in combination with corneal cross-linking, which may have a further influence on the corneal astigmatism. In addition, the ablation depth in keratoconus is most likely limited to 40 to 50 μm, so it may not be possible to perform the full ablation as desired. Both of these factors make the application of the suggested strategy conditional and less applicable. For determining the cylinder for the toric IOL used in eyes with coma-dominated corneal optics, one should ideally be able to precisely calculate the astigmatic effect of the corneal coma and use that value along with the TCA to calculate the IOL cylinder by vector analysis. So far, no clinically useful method for estimating the astigmatic effect of the corneal coma has been developed.

To our knowledge, this is the first study to specifically investigate the astigmatism correction strategy in treatment of the eyes with coma-dominant corneal optics by topography-guided corneal refractive surgery and lenticular exchange surgery. Our study reveals that, in cases with significant coma or coma-like HOAs and low estimated lenticular astigmatism, topography-guided custom ablation aiming to correct TCA independent of MRC is preferable, whereas in lenticular exchange surgery, the toric IOL cylinder, which aims to correct MRC, appears preferable. The applicability of the strategy should be limited to cases where the contribution of lenticular astigmatism to MRC is estimated to be less than the contribution of coma-like HOAs.

AUTHOR CONTRIBUTIONS

Study concept and design (WZ, AS); data collection (WZ); analysis and interpretation of data (WZ, FS, DZR, TJA, XC, TPU, YF, AS); writing the manuscript (WZ, FS, AS); critical revision of the manuscript (WZ, DZR, TJA, XC, TPU, YF, AS); statistical expertise (WZ, FS, DZR, TJA, XC); administrative, technical, or material support (YF); supervision (XC, TPU, AS)

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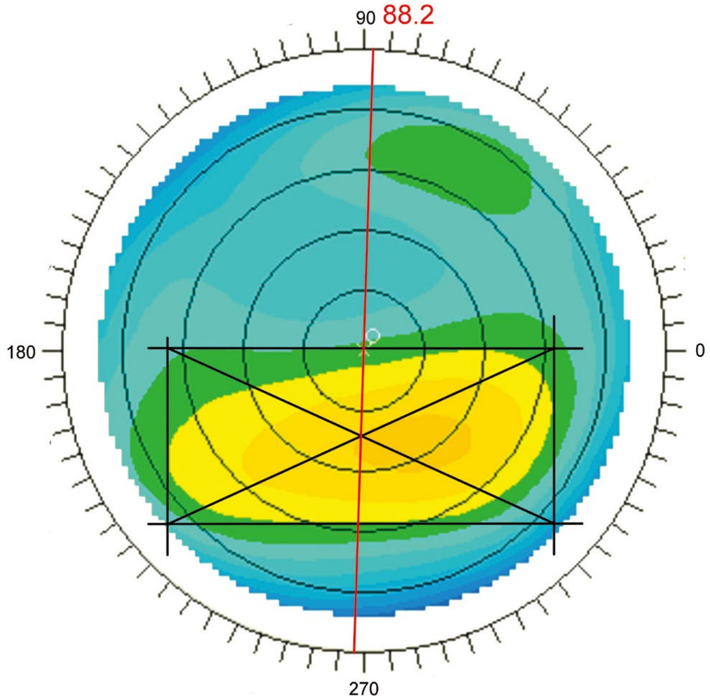

Figure 1. Defining coma axis. The area of coma was defined by two vertical and two horizontal lines that are touching the most outer points of the yellow area superiorly, inferiorly, nasally, and temporally. The intersection of the rectangular diagonals is considered to be the center of coma. The axis passing through both the corneal vertex and the coma center is considered the axis of coma.

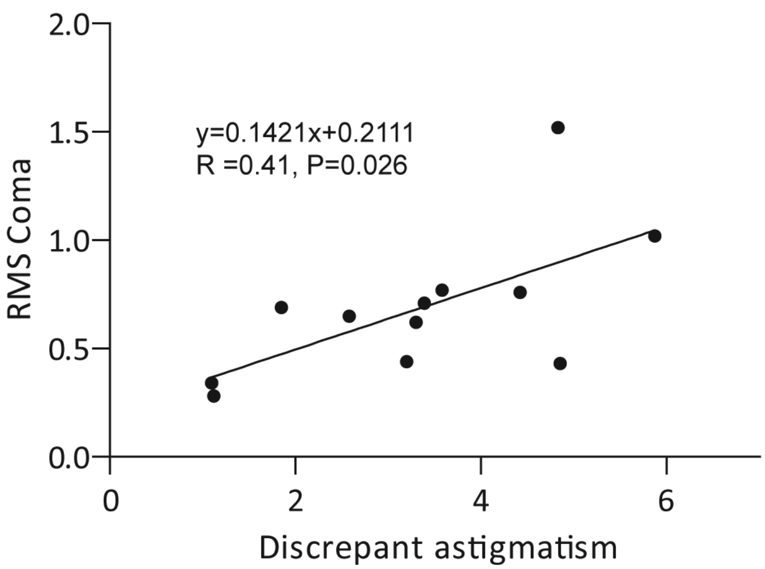

Figure 2. Correlation between magnitudes of discrepant astigmatism (x-axis) and coma (y-axis). RMS = root mean square

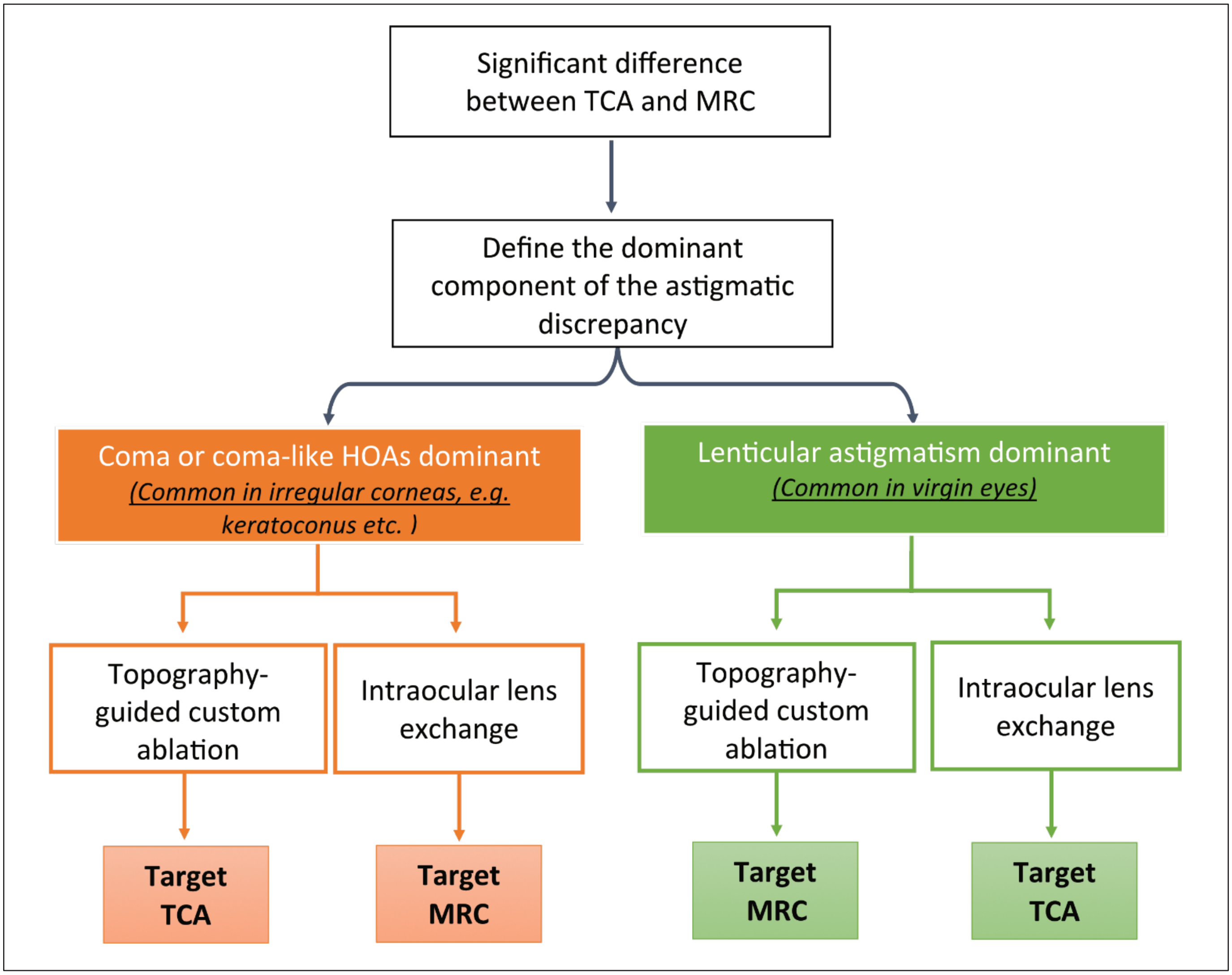

Figure 3. Flow chart for correction of astigmatism with significant difference between total corneal astigmatism (TCA) and manifest refractive cylinder (MRC) in topography-guided ablation and toric intraocular lens exchange in virgin eyes, and in corneas with coma-dominant irregular optics (where astigmatic influence of coma on manifest refractive cylinder is higher than influence of lenticular astigmatism). HOAs = higher order aberrations

TABLE 1
Astigmatic Components and RMS Coma, and Their Effect on OA and MRC Orientation in the 12 Cases

No.	MRC (D)	MRC (°)	TCA (D)	TCA (°)	LA (D)	LA (°)	OA (D)	OA (°)	DA (D)	DA (°)	RMS Coma (µm)[a]	Coma (°)	OA	MRC
Group 1														
1	-2.61	90	-1.86	11	-0.93	38	-2.52	20	-4.83	100	1.52	87 (V)	WTR	ATR
2	-2.58	82	-1.24	23	-0.86	42	-1.99	30	-3.58	98	0.77	87 (V)	WTR	ATR
3	-2.04	95	-1.60	180	-0.39	68	-1.35	6	-3.39	95	0.71	85 (V)	WTR	ATR
4	-4.59	87	-1.55	154	-0.45	31	-1.43	162	-5.87	84	1.02	79 (V)	WTR	ATR
5	-2.31	82	-2.67	21	-0.39	145	-2.55	17	-4.42	95	0.76	89 (V)	WTR	ATR
6	-1.50	90	-1.87	161	-0.74	33	-1.83	173	-3.30	86	0.62	88 (V)	WTR	ATR
7	-1.96	85	-1.76	20	-0.18	101	-1.59	21	-3.20	97	0.44	118 (V)	WTR	ATR
Group 2														
1	-3.68	95	-1.86	11	-0.99	21	-2.42	108	-1.85	77	0.69	100 (V)	ATR	ATR
2	-1.12	170	-1.24	23	-0.55	70	-2.20	174	-1.10	88	0.34	110 (V)	WTR	WTR
3	-3.07	2	-1.60	180	-1.43	117	-2.52	62	-4.85	169	0.43	20 (H)	ATR	WTR
4	-1.03	-70	-1.55	154	-0.56	74	-1.59	171	-2.58	77	0.65	81 (V)	WTR	ATR
5	-2.23	105	-2.67	21	-0.67	115	-1.11	108	-1.12	102	0.28	94 (V)	ATR	ATR

RMS = root mean square; OA = ocular astigmatism; MRC = manifest refractive cylinder; D = diopters; ° = axis degrees; TCA = total corneal astigmatism; LA = lenticular astigmatism; DA = discrepant astigmatism; group 1 = topography-guided refractive surgery; V = vertical; WTR = with the rule; ATR = against the rule; group 2 = lenticular exchange surgery with toric intraocular lens implantation; H = horizontal
[a]*At 3.5-mm diameter.*

TABLE 2
Estimated Postoperative Manifest Refractive Cylinder

No.	Strategy 1		Strategy 2	
	Amplitude (Diopters)	Axis (Degrees)	Amplitude (Diopters)	Axis (Degrees)
Group 1				
1	-0.93	38	-4.45	5
2	-0.86	42	-3.35	2
3	-0.39	68	-4.00	2
4	-0.45	31	-5.90	92
5	-0.39	145	-4.42	8
6	-0.74	33	-2.97	169
7	-0.18	101	-3.36	7
Group 2				
1	-1.85	77	-0.99	111
2	-1.10	87	-0.55	160
3	-4.85	169	-1.43	27
4	-2.58	77	-0.56	164
5	-1.12	102	0.67	25

group 1 = topography-guided refractive surgery; group 2 = lenticular exchange surgery with toric intraocular lens implantation; strategy 1 in group 1 = correction of total corneal astigmatism along with corneal HOAs; strategy 2 in group 1 = correction of manifest refractive cylinder along with corneal higher order abberations; strategy 1 in group 2 = correction of total corneal astigmatism; strategy 2 in group 2 = correction of manifest refractive cylinder

TABLE A

Abbreviations and Explanations for Various Astigmatic Components

Abbreviation	Full Name	Description	Obtaining Method	Measurement/Calculation Method
Measured astigmatism				
MRC	Manifest refractive cylinder	Subjectively perceived magnitude and axis of astigmatism	Non-cycloplegic manifest refraction	MRC was first converted to cross-cylinder notation, and then transferred from the spectacle plane using a vertex distance of 12 mm
TCA	Total corneal astigmatism	Sum of anterior and posterior corneal topographic astigmatism	Directly provided by Precisio topographer	Ray-tracing
PCA	Posterior corneal astigmatism	Astigmatism contributed by posterior surface of cornea	Directly provided by Precisio topographer	Ray-tracing
IA	Internal astigmatism	Astigmatism contributed by internal eye (ie, sum of astigmatism from posterior cornea and crystalline lens)	Directly provided by OPD-Scan II	Combining optical path difference-based wavefront aberrometry and Placido disk technology
Estimated astigmatism				
LA	Lenticular astigmatism	Astigmatism contributed by crystalline lens	Precisio topographer and OPD-Scan II	Vector analysis (internal A minus posterior A)
OA	Ocular astigmatism	Total astigmatism from both cornea (anterior and posterior cornea) and crystalline lens	Precisio topographer and OPD-Scan II	Vector analysis (TCA+LA)
ORA	Ocular residual astigmatism	Difference between corneal topographic astigmatism and manifest refractive cylinder	Introduced by Alpins	Vector analysis

The Precisio is is manufactured by iVIS Technology and the OPD-Scan II is manufactured by NIDEK.

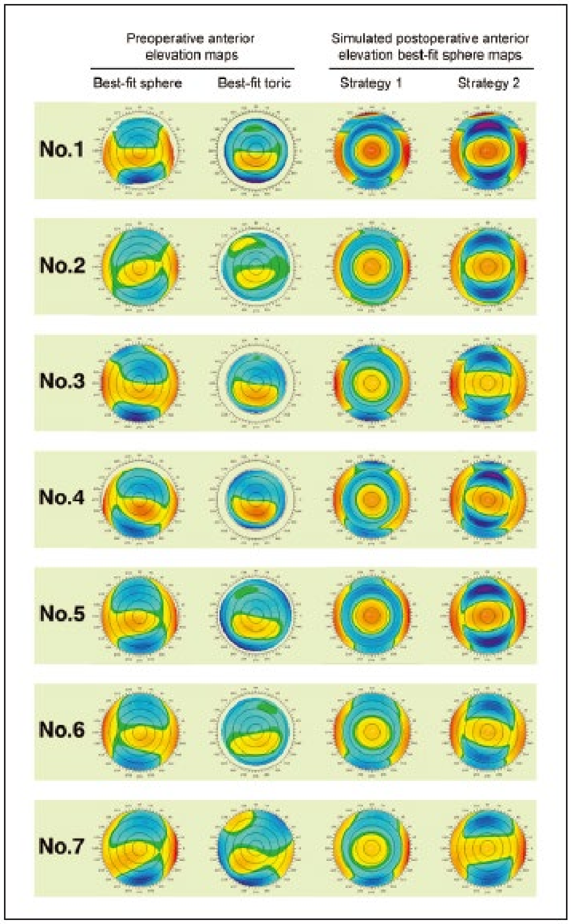

Figure A. Preoperative and simulated postoperative anterior corneal elevation maps in the topography-guided group. Preoperative anterior elevation maps: best-fit sphere (column 1), best-fit toric (column 2), and simulated postoperative anterior elevation best-fit sphere maps after strategies 1 and 2 (column 3 and column 4, respectively).

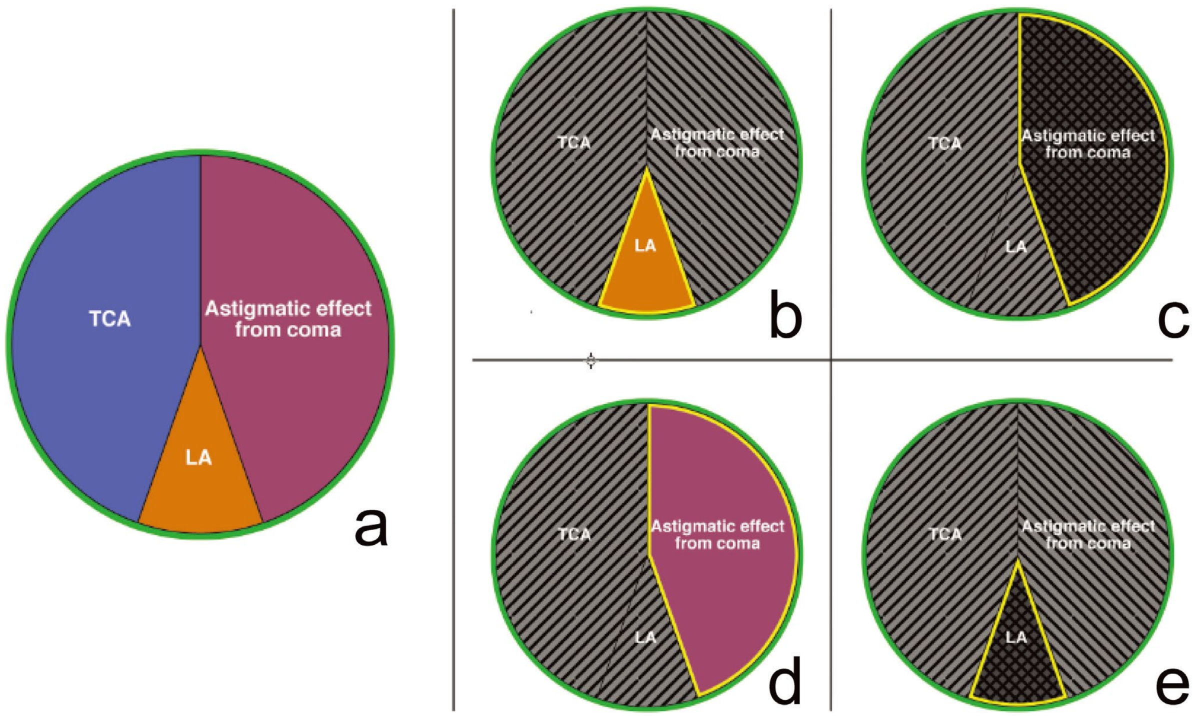

Figure B. Astigmatic components contributing to manifest refractive cylinder (MRC) in eyes with coma-dominant corneal optics and the effects of different treatment strategies on estimated postoperative MRC (outlined in yellow). (A) Preoperative astigmatic components in eyes with coma-dominant corneal optics. (B) Estimated postoperative MRC with strategy 1 in the topography-guided group (topography-guided ablation treating total corneal astigmatism (TCA) along with coma and its astigmatic influence, resulting in uncorrected lenticular astigmatism (LA). (C) Estimated postoperative MRC with strategy 2 in the topography-guided group (topography-guided ablation treating MRC along with coma and its astigmatic contribution, resulting in double correction of the astigmatic contribution of coma). (D) Estimated postoperative MRC with strategy 1 in the toric IOL group (toric lenticular exchange surgery treating TCA, resulting in uncorrected astigmatic contribution of coma). (E) Estimated postoperative MRC with strategy 2 in the toric intraocular lens group (toric lenticular exchange surgery treating MRC, resulting in double correction of LA). *Assumption: LA<Astigmatic influence of coma