Clinical Effects of Pure Cyclotorsional Errors during Refractive Surgery

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Purpose. To describe the theoretical effects of cyclotorted ablations on induced aberrations and determine the limits of tolerance of cyclotorsional accuracy.

Methods. A method was developed to determine the average cyclotorsion during refractive surgery without a cyclotorsion tracker. Mathematical conditions were simulated to determine the optical, visual, and absolute benefits in 76 consecutive treatments performed on right eyes. The results were evaluated as Zernike expansion of residual wavefront aberrations.

Results. Ablations based purely on Zernike decomposition but with cyclotorsion applied resulted in residual aberrations of the same Zernike modes of different magnitudes and orientations, indicating that the effect of cyclotorted compensation can be analyzed by single Zernike modes in magnitude and orientation. The effect on single Zernike modes depends on angular frequency, and not on radial order. A mean of 4.39° of cyclotorsion was obtained. A theoretical optical benefit was achieved in 95% of treatments, a theoretical visual benefit in 95%, and an absolute benefit in 93% compared with 89%, 87%, and 96% of treatments achieving actual benefits, respectively.

Conclusions. Residual aberrations resulting from cyclotorsion depend on aberrations included in the ablation and cyclotorsional error. The theoretical impact of cyclotorted ablations is smaller than that of decentered ablations or edge effects in coma and spherical aberrations. The results are valid within a single-failure condition of pure cyclotorsional errors, because no other sources of aberrations are considered. The leap from the mathematical model to the real-world outcome cannot be extrapolated without further study. (*Invest Ophthalmol Vis Sci.* 2008;49:4828–4836) DOI:10.1167/iovs.08-1766

Human eyes have 6 degrees of freedom to move: *x*/*y* lateral shifts, *z* leveling, horizontal/vertical rotations, and cyclotorsion (rotations around the optical axis).

Laser technology for refractive surgery allows corneal alterations that correct refractive errors[1] more accurately than ever. Ablation profiles are based on the removal of tissue lenticules in the form of sequential laser pulses that ablate a small amount of corneal tissue to compensate for refractive errors. However, the quality of vision can deteriorate significantly, especially under mesopic and low-contrast conditions.[2]

Induction of aberrations, such as spherical aberrations and coma, is related to loss of visual acuity (VA)[3] and quality. Some aberrations, however, may be subject to neural adaptation. Artal et al.,[4] in a study of the effects of neural compensation on vision, indicated that visual quality in humans is superior to the optical quality provided by the human eye.

To balance already existing aberrations, customized treatments were developed that use either wavefront measurements of the whole eye[5] (obtained, e.g., by Hartmann-Shack wavefront sensors) or corneal topography–derived wavefront analysis.[6,7] Topography-guided,[8] wavefront-driven,[9] wavefront-optimized,[10] asphericity preserving, and Q-factor profiles[11] have been proposed as solutions.

Measuring rotation when the patient is upright compared with when the refractive treatments are performed with the patient supine may lead to ocular cyclotorsion,[12] resulting in mismatching of the applied versus the intended profiles[13] (Fig. 1). Recently, some equipment has been developed that can facilitate measurement of and potential compensation for static cyclotorsion that occurs when the patient moves from the upright to the supine position during the procedure.

In the present study, we examined the effects of pure uncompensated cyclotorsional errors during refractive surgery.

Methods

Determination of Cyclotorsion during Refractive Surgery

The study was conducted in accordance with the Declaration of Helsinki.

All surgeries were performed by one surgeon (DO), flaps were created using a microkeratome (Pendular; Schwind Eye-Tech-Solutions GmbH, Kleinostheim, Germany), and ablations were performed with a system that delivers aberration-free profiles (ESIRIS; Schwind Eye-Tech-Solutions GmbH).

We analyzed the topographies using the Keratron-Scout videokeratoscope (Optikon2000 S.p.A, Rome, Italy), before surgery and 3 months after LASIK, and measured the Maloney indices in 76 consecutive right eyes with myopic astigmatism. Using only right eyes or only left eyes simplifies calculations because it directly avoids considering potential bilateral symmetry effects of cyclotorsion between eyes (i.e., cyclotorsional values in the left eye might be multiplied by −1).

As reported previously,[14] the achieved correction after refractive surgery can be calculated from the topographic changes. The vectorial differences in the astigmatic space between the postoperative and preoperative Maloney indices[14,15] were compared to the intended corrections—for example, a preoperative topography of 41.6 D at 111° and 41.2 D at 21° and a postoperative topography of 44.4 D at 114° and 43.5 D at 24° results in a spherical change of +3.0 D with a cylindrical component of −0.5 D at 117° compared with the planned +3.0 D, −0.5 D × 110° at the 12-mm vertex distance, resulting in 7° of counterclockwise cyclotorsion (Fig. 2). Maloney indices use the inner 3-mm zone, to fit this disc area best to a spherocylindrical surface in 3 dimensions. Cylinder orientation defines the two principal meridians, and sphere and cylinder provide the curvatures of the principal me-

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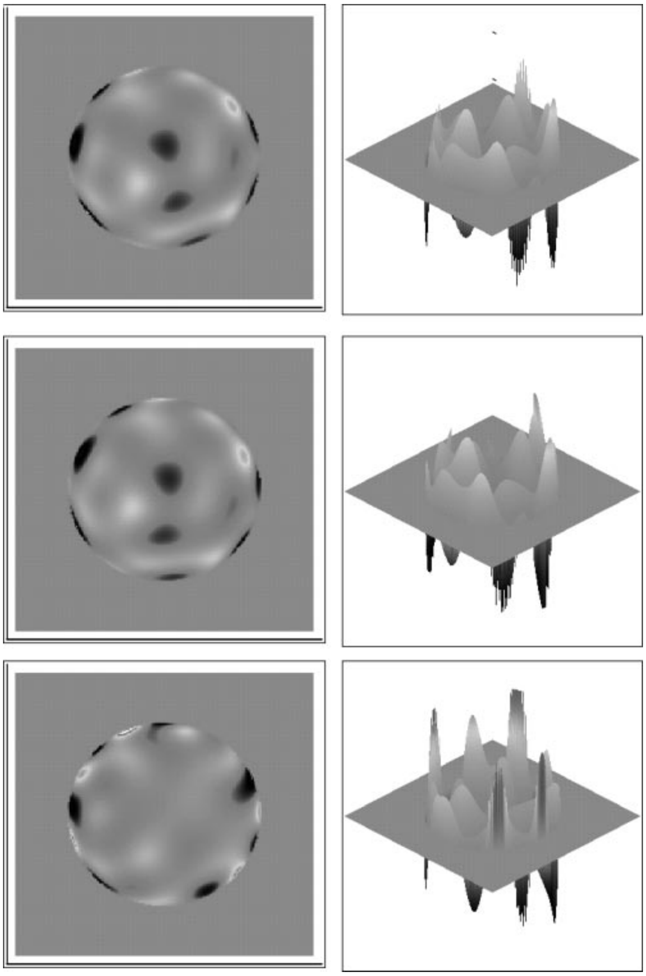

FIGURE 1. *Top*: Original wavefront error; *middle*: 15° clockwise torted wavefront error; *bottom*: residual wavefront error (all in two dimension and three dimensions).

ridians. In normal corneas (without irregular astigmatism) sim-K and Maloney analyses provide very similar results.

Residual Aberration after Cyclotorsional Errors during Refractive Surgery

When the rotation angle is 0, the aberration and compensation patterns cancel each other, resulting in no residual aberration. Based on the definition of the Zernike polynomials[16] ($Z(n,m)$, where n is a null or positive integer and m is an integer ranging from $-n$ to $+n$, representing the radial and meridional orders, respectively), it is evident that the polynomials $Z(n,0)$ are invariant under rotations around their center. The only aberrations affected by cyclotorsional errors are vectorial. For those, Zernike polynomials are structured in two complementary sets, governed by sine/cosine functions that avoid coupling of different orders of aberration for rotations around the center.

After rotation of the opposite Zernike components around their origins, the aberration mode still can be decomposed into two Zernike components:

$$C'^{m}_{n} = -[C_n^{m}\cos(m\theta) + C_n^{-m}\sin(m\theta)]. \qquad (1)$$

where n is the radial order; m, the angular frequency; C'^{m}_{n}, the rotated Zernike compensation; $C_n^{\pm m}$, the original Zernike components; and θ, the cyclotorsional angle.

After compensating for the original pattern with a rotated one, the residual components are:

$$C''^{m}_{n} = C_n^{m}[1 - \cos(m\theta)] - C_n^{-m}\sin(m\theta), \qquad (2)$$

where C''^{m}_{n} is the residual Zernike component.

Expressing each aberration in magnitude and orientation[17]:

$$|C''_{nm}| = |C_n^{\pm m}|\,2\sin\left(\frac{m\theta}{2}\right) \qquad (3)$$

and

$$\Delta\alpha = \alpha - \alpha_0 = \frac{\theta}{2} - \frac{\pi}{2m}. \qquad (4)$$

According to the previous example, a planned correction of +3.0, –0.5 D × 110° at the 12-mm vertex distance and an actual spherical change of +3.0 D with a cylindrical component of −0.5 D at 117° results in 7° of counterclockwise cyclotorsion and would lead to a postoperative refraction of +0.07, −0.13 D × 69°.

The relative amount of residual aberrations depends only on cyclotorsional error (Figs. 3, 4). Since the original aberration can be described as a linear combination of Zernike polynomials[16] and each of these Zernike terms results in a residual Zernike term after partial compensatory rotation, the residual wavefront aberration is the sum of all residual terms.

Derivation of a Mathematic Condition to Determine an Optical Benefit

A condition in which any postoperative aberration smaller than its preoperative magnitude was considered positive was referred to as an optical benefit:

$$2\left|\sin\left(\frac{m\theta}{2}\right)\right| < 1 \qquad (5)$$

and

$$|m| < \frac{2\arcsin(½)}{|\theta|} < \left|\frac{\pi}{3\theta}\right|. \qquad (6)$$

According to this example, 7° of cyclotorsion would produce an optical benefit up to the octafoil angular frequencies.

Considering the cyclotorsional error and the preoperative astigmatism, we calculated how many treatments would theoretically achieve an optical benefit for the astigmatism component ($m = 2$). Because the treatments were planned as aberration-free profiles and therefore were based only on sphere, cylinder, and axis inputs, the astigmatism was the only vectorial aberration included. Moreover, astigmatism is in magnitude the major Zernike mode of a vectorial nature. We compared this value to the percentage of eyes that actually obtained a postoperative cylinder lower than the preoperative value.

Derivation of a Mathematic Condition to Determine a Visual Benefit

To distinguish between optical benefit (merely reducing the aberration magnitude) and visual performance (visual benefit), we adopted a model based on the findings of Artal et al.[4] In their study, equivalent human optical systems that differed only in the orientation of the aberration patterns (produced by adaptive optics) achieved different visual performances mainly due to neural compensation for the unique aberration pattern of each individual. For that reason, matching factor (MF) behavior based on single aberrations was modeled. MF is at its maximum (equal to 1) in aberrations of the same orientation and at its minimum for aberrations of the opposite orientation in the Zernike

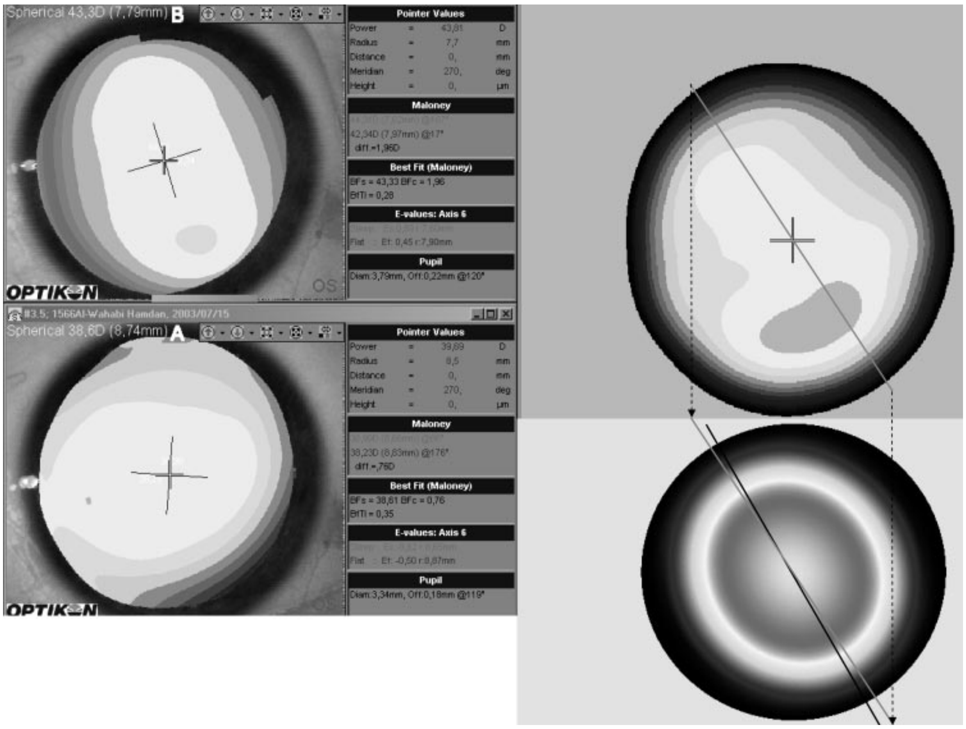

FIGURE 2. The difference between the postoperative and preoperative topographies compared to the intended correction. The difference in the orientation of the astigmatism defines the cyclotorsional error. (**A**) Preoperative topography, (**B**) postoperative topography, (*top right*) differential topography, (*bottom right*) planned correction. Counterclockwise torsion of the astigmatism can be seen.

space. The magnitude of aberration distribution was considered as a decreasing exponential with the Zernike order as described by Thibos et al.[18]

Visual benefit was defined as a condition in which the postoperative aberration was smaller than its preoperative magnitude times the MF for that relative orientation:

$$2\left|\sin\left(\frac{m\theta}{2}\right)\right| < MF + (1 - MF)\left|\cos(m\Delta\alpha)\right| \qquad (7)$$

and

$$|m| < \frac{2\arcsin\left(\dfrac{MF}{MF+1}\right)}{|\theta|}. \qquad (8)$$

The arbitrary value of 0.625 was chosen as the MF generator; this value produces a maximum equal to 1 and a minimum equal to 0.25 (Fig. 5):

$$MF = 0.625 \qquad (9)$$

and

$$|m| < \frac{2\arcsin(5/13)}{|\theta|}. \qquad (10)$$

According to this example, 7° of cyclotorsion would produce a visual benefit up to the hexafoil angular frequencies.

With the cyclotorsional error and the preoperative astigmatism and assuming that cyclotorsional errors around the ablation center were the only failure, the number of eyes was calculated that would have

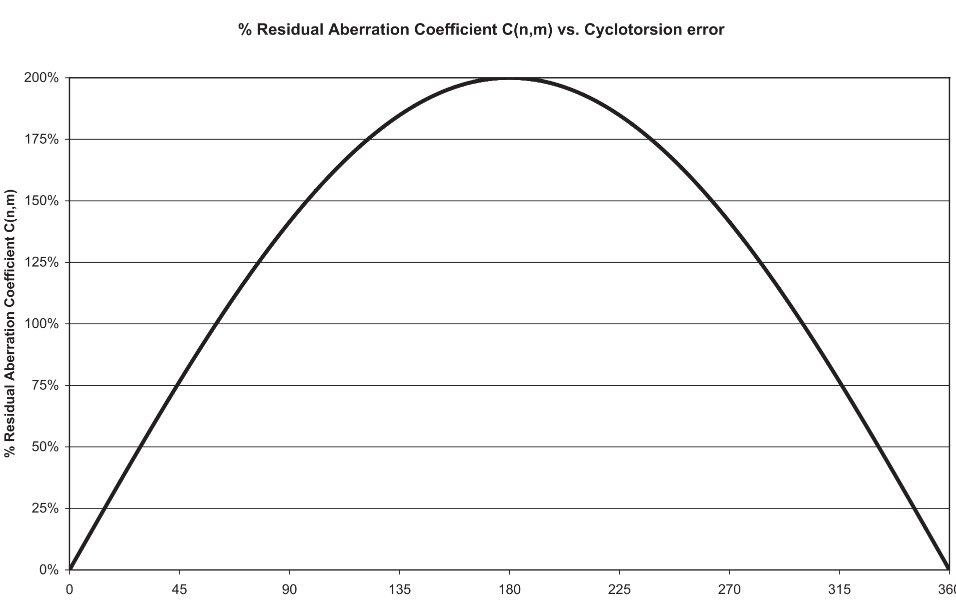

FIGURE 3. The percentage of residual aberrations versus cyclotorsional error. Modulation of the cyclotorsional error by the angular frequency (m) is shown; the higher the angular frequency, the faster the residual aberration varies. For $m = 1$ (coma), the maximum residual error is achieved for 180° torsion; for $m = 2$ (cylinder), the maximum residual error would be achieved for 90° torsion; for $m = 3$ (trefoil), the maximum residual error would be achieved for 60° torsion, and so on.

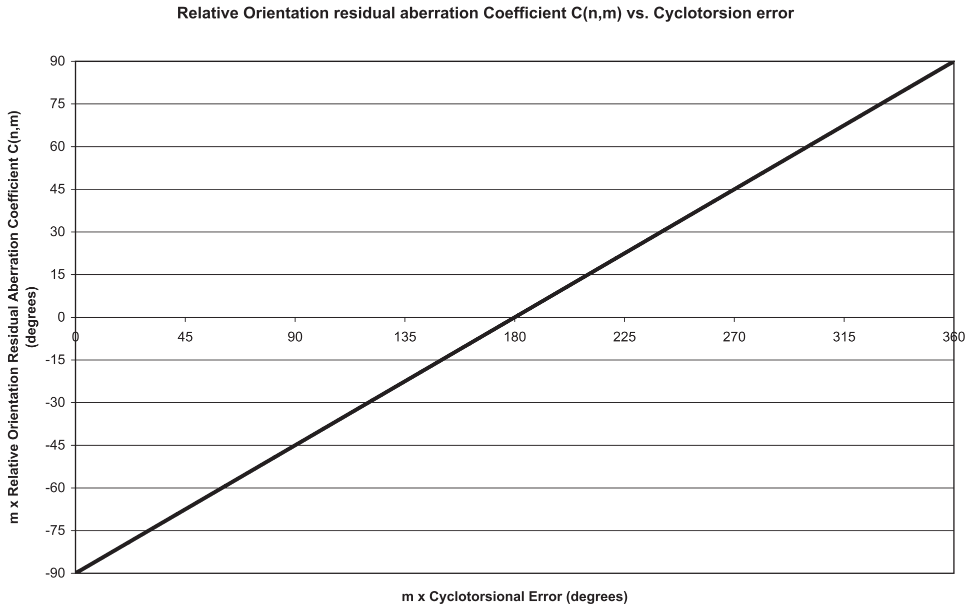

FIGURE 4. The relative orientation of residual aberrations versus cyclotorsional error. Modulation of the cyclotorsional error and the relative orientation by the angular frequency (*m*) are shown.

obtained a visual benefit for cylinder if the correction were correct but the axis was incorrect. We compared this value to the percentage of eyes in which postoperative uncorrected visual acuity (UCVA) was maintained or improved, compared with the preoperative best spectacle-corrected visual acuity (BSCVA) and with the percentage of eyes with actually maintained or improved BSCVA.

Derivation of a Mathematic Condition to Determine an Absolute Benefit

The major ocular aberrations are defocus and primary astigmatism, which is the major aberration affected by a rotational error. The amount of tolerable residual astigmatism after surgery cannot be defined as a percentage of the preoperative astigmatism, because the tolerance limit is set by the image-forming characteristics of the eye and so takes an absolute value. With simple spherical error, degradation of resolution begins, in most people, with errors of 0.25 D. A similar measure can be placed on the error due to cylinder axis error.[19]

A simple approach for classifying the clinical relevance of single aberration terms was proposed by Thibos et al.,[20] who introduced the concept of equivalent defocus[20] (DEQ) as a metric to minimize the differences in the Zernike coefficients due to different pupil sizes.

DEQ is defined as the amount of defocus that produces the same wavefront variance as that found in one or more higher order aberrations:

$$DEQ_{nm} = \frac{16\sqrt{3}\,|C_{nm}|}{AD^2}, \qquad (11)$$

where AD is the diameter considered for the wavefront aberration analysis

The absolute benefit considers as positive any result for which the postoperative aberration pattern was smaller than an absolute limit of 0.50 DEQ for the magnitude of each Zernike mode (i.e., a ±0.25 DEQ maximum deviation in one or several meridians).

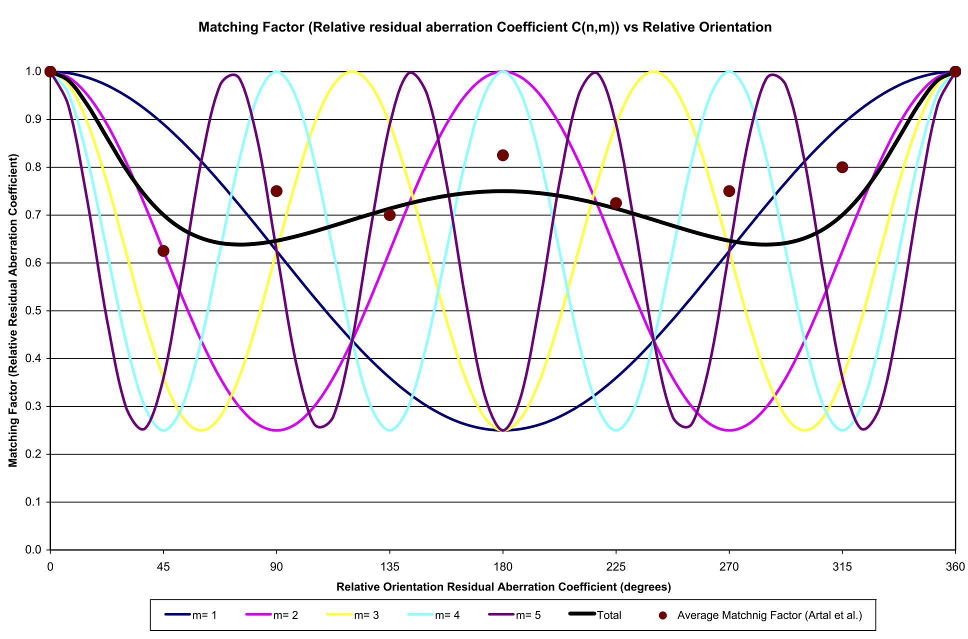

FIGURE 5. Matching factor versus relative orientation of residual aberrations. These data agree with those of Artal et al.[4]

The absolute benefit is ruled by the condition

$$\left| DEQ_{nm} 2 \sin\left(\frac{m\theta}{2}\right)\right| < 0.50 \qquad (12)$$

and

$$|DEQ_{nm}| < \frac{1}{4\left|\sin\left(\frac{m\theta}{2}\right)\right|}. \qquad (13)$$

According to this example, 7° of cyclotorsion, Zernike modes should not exceed 4.10 DEQ for coma, 2.05 DEQ for astigmatism, and 1.37 DEQ for trefoil, for theoretically successful results.

With the torsional error and the preoperative astigmatism and assuming that cyclotorsion around the ablation center was the only failure, the number of eyes was calculated that would have obtained an absolute benefit for cylinder (postoperative magnitude, ≤0.50 D) if the cylindrical correction were correct but the axis was wrong. We compared this value to the eyes in which postoperative astigmatism was less than 0.50 D.

Results

Static Cyclotorsion during Laser Refractive Surgery

Preoperative and postoperative topographies were compared 3 months after treatment in 76 consecutives right eyes treated without adverse events at Augenzentrum Recklinghausen.

The preoperative spherical equivalent (SE) was −3.56 D with a standard deviation (SD) of 1.51 D (range, −7.00 to −1.25 D), sphere, −3.15 ± 1.48 D (−6.50 to −0.50 D); and cylinder, −0.82 ± 0.66 D (−3.00 to −0.25 D).

The distribution of the attempted astigmatic correction is shown in Figure 6; 30% of the treatments (n = 23) had corrections of −0.25 D of astigmatism, 20% (n = 15) corrections of −0.50 D of astigmatism, 39% (n = 30) corrections between −0.75 and −1.50 D of astigmatism, and 11% (n = 8) corrections between −1.50 and −3.00 D of astigmatism.

At the 3-month follow-up, the mean SE was −0.14 ± 0.30 D (range, −1.00 to +0.25 D); sphere, −0.06 ± 0.29 D (−0.75 to +0.25 D); and cylinder, −0.17 ± 0.26 D (−1.25 to 0.00 D). Eighty-seven percent of the eyes (n = 66) were within ±0.50 D of the attempted correction, and 100% (n = 76) were within ±1.00 D.

The direct average of the cyclotorsional errors was 2.42°, whereas the absolute error averaged 4.39°. Figure 7 is a stratification of the cyclotorsional error expressed in absolute values. Seventy-one percent of the eyes (n = 54) had less than 2.5° of cyclotorsion, 78% (n = 59) less than 5.0°, and 87% (n = 66) less than 10.0°.

Theoretical Ranges for Optical, Visual, and Absolute Benefits

The maximum angular frequency and Zernike mode magnitudes that fulfill these conditions were calculated for specific cyclotorsional errors (Fig. 8, Tables 1, 2), but for the description of the magnitudes, we focused on astigmatism, coma, and trefoil because these are the major Zernike modes of a vectorial nature.

For cyclotorsional errors up to ±14°, it is possible to obtain a visual benefit for comatic, astigmatic, and trefoil angular frequencies and an optical benefit for tetrafoil angular frequencies, as well. It also is possible to control the creation of blur under an absolute limit whenever coma magnitudes do not exceed 2.05 DEQ; astigmatism, 1.03 D; and trefoil, 0.70 DEQ.

For maximum cyclotorsional errors up to ±4°, the theoretical limit for visual benefit extends up to endecafoil (11-fold) angular frequencies and for optical benefit up to 15-fold (pentadecafoil) angular frequencies. The magnitudes for the major Zernike modes should not exceed 7.16 DEQ for coma, 3.58 DEQ for astigmatism, and 2.39 DEQ for trefoil.

For cyclotorsional errors up to ±1.5°, visual benefit extends up to triacontafoil (30-fold) angular frequencies and optical benefit even beyond these frequencies. Moreover, coma magnitudes below 19.10 DEQ, astigmatism up to 9.55 D, and trefoil up to 6.37 DEQ produce a postoperative blur under 0.50 DEQ.

Table 3 summarizes the residual aberration ratios and relative orientations for different cyclotorsional errors. The percentage is the amount of postoperative residual in magnitude, and the angle is the relative orientation of the postoperative residual. For example, 1.00 μm of trefoil at 30° with a 5° clockwise torsional error results a postoperative residual error of 0.26 μm of trefoil at 58°, or 3.00 DEQ astigmatism at 75° with a 10° counterclockwise torsional error results in a postoperative residual error of 1.04 DEQ astigmatism at 35°.

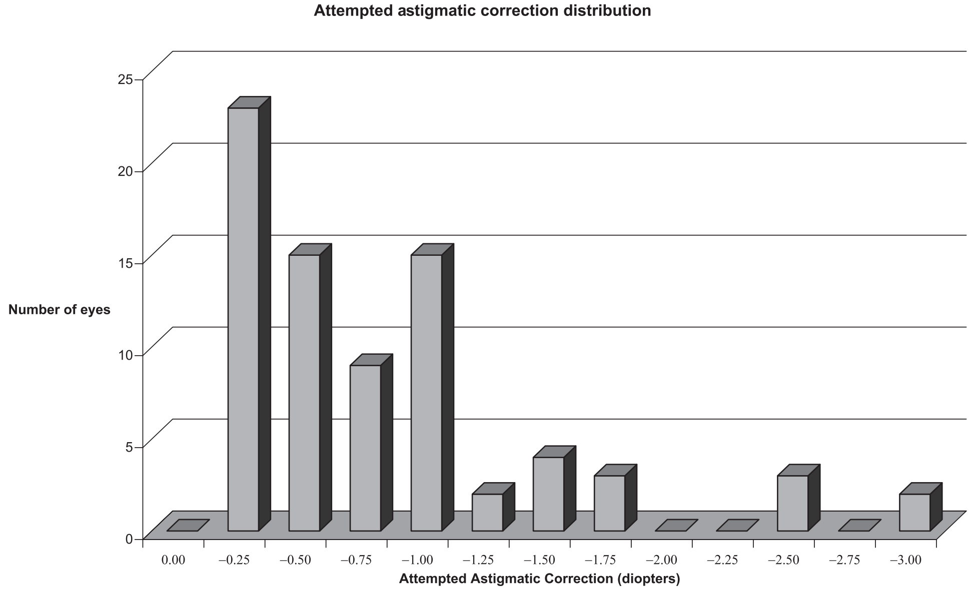

Figure 6. Distribution of the magnitudes of the attempted astigmatic correction.

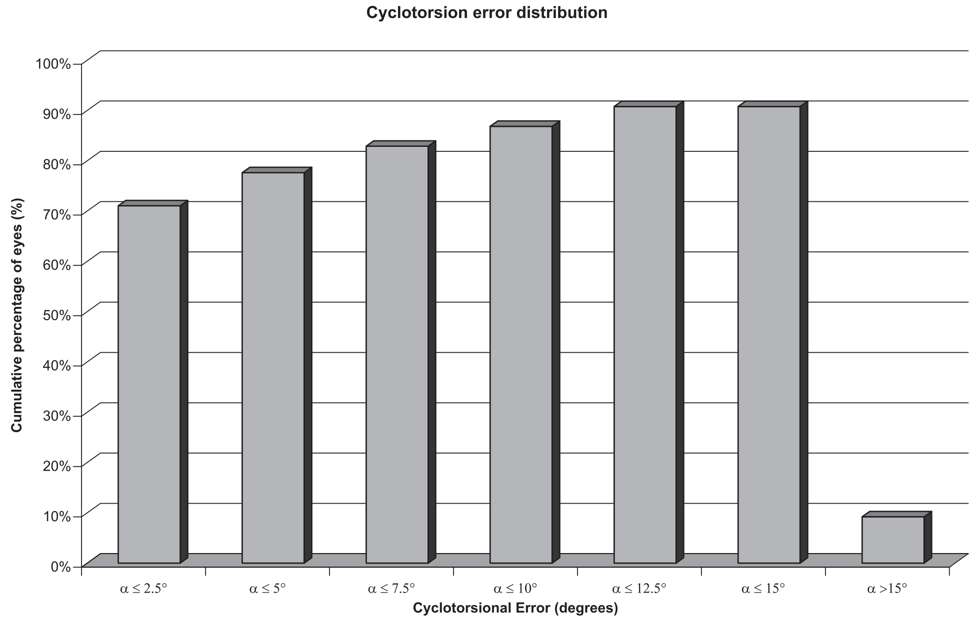

FIGURE 7. Distribution of the retrospectively calculated cyclotorsional errors.

Clinical Optical Benefit

Considering the cyclotorsional error and the preoperative astigmatism, we calculated the number of treatments that would theoretically achieve an optical benefit for the astigmatism component ($m = 2$).

With these settings, 95% of the eyes ($n = 72$) would have obtained an optical benefit for the cylinder if the cylindrical correction were correct but the axis was wrong and if cyclotorsional errors occurring around the ablation center were the only failures. This compared with 89% of the eyes ($n = 68$) that actually obtained a postoperative cylinder lower than preoperative value. The differences between the theoretical and the empiric results were marginally significant ($P = 0.05$).

Clinical Visual Benefit

With the same settings as previously, 95% of the eyes ($n = 72$) would have obtained a visual benefit for the cylinder compared with 87% of the eyes ($n = 66$) that actually had a stable or improved postoperative UCVA compared with the preoperative BSCVA ($P < 0.01$) and with 91% of the eyes ($n = 69$) with a stable or improved BSCVA ($P = 0.09$).

Clinical Absolute Benefit

With the same settings as previously, 93% of the eyes ($n = 71$) would have obtained an absolute benefit for the cylinder compared with 96% of the eyes ($n = 73$) in which the postoperative astigmatism was smaller than 0.50 D ($P = 0.21$).

Clinical Ranges for Optical, Visual, and Absolute Benefits

Combining all success ratios to calculate the number of eyes that obtained (theoretically and empirically) optical, visual, and absolute benefits simultaneously, 89% of the eyes ($n = 68$) with theoretical global success vs. 79% of the eyes ($n = 60$) obtained a postoperative cylinder lower than that before sur-

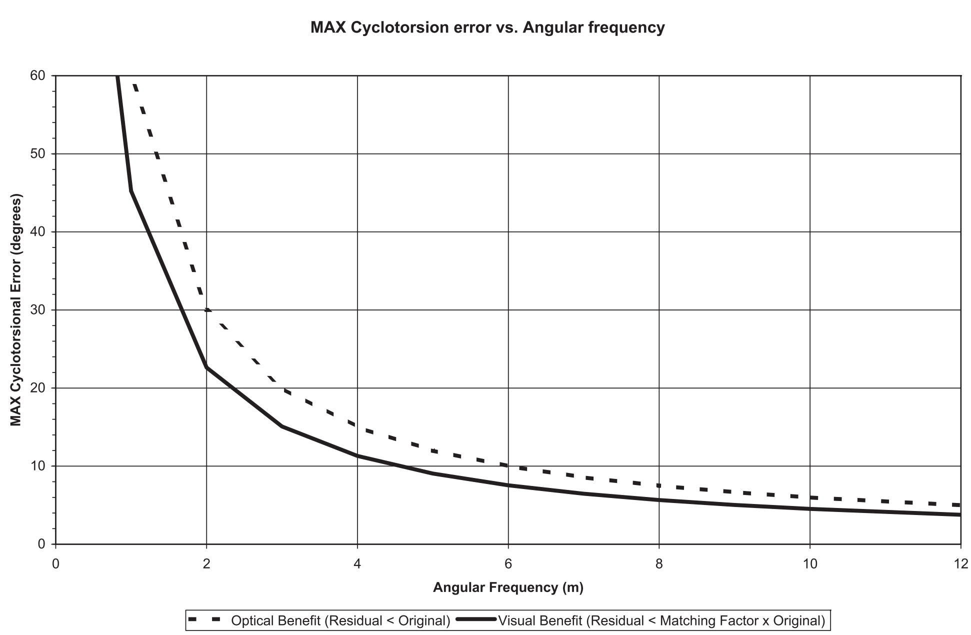

FIGURE 8. The maximum allowable cyclotorsional errors versus angular frequency for different criteria.

Table 1. Maximum Allowable Cyclotorsional Errors for Different Aberration Components and Different Criteria

Aberrations	*m*	Optical Benefit (Residual < Original)	Visual Benefit (Residual < Matching Factor)
Coma	1	60.0	45.2
Astigmatism	**2**	**30.0**	**22.6**
Trefoil	3	20.0	15.1
Tetrafoil	4	15.0	11.3
Pentafoil	5	12.0	9.0
Hexafoil	6	10.0	7.5
Heptafoil	7	8.6	6.5
Octafoil	8	7.5	5.7
Eneafoil	9	6.7	5.0
Decafoil	10	6.0	4.5
Dodecafoil	12	5.0	3.8
Pentadecafoil	15	4.0	3.0
Icosafoil	20	3.0	2.3
Triacontafoil	30	2.0	1.5
Hexacontafoil	60	1.0	0.8

In bold: astigmatism, as it is the major aberration mode with a vector nature.

gery, lower than 0.50 D, and a stable or improved BSCVA ($P < 0.005$).

Considering the cyclotorsional error, we calculated a hypothetical case simulating the condition in these patients, for which Zernike mode the treatments could have been planned to achieve optical and visual benefits (Table 4).

Discussion

The method used in this study to determine the cyclotorsional error incurred during laser refractive surgery is indirect, because it calculates the torsional error retrospectively after the ablation procedures have been performed. However, it is easy and straightforward and does not require additional equipment or complicated algorithms. Its retrospective nature ensures that the calculated error corresponds to the average cyclotorsional error during the entire refractive surgery procedure. This way, the method could be used to validate the cyclotorsional errors obtained with other prospective methods.

The study had limitations. Because the method considers that the difference between the planned astigmatism axis and the axis of the effectively achieved cylindrical correction is due only to cyclotorsional errors, it may be affected by other sources of unavoidable errors in laser refractive surgery, such as flap cuts, pattern decentration, blending zones, and corneal biomechanics. The results are valid in the absolute single-failure condition of pure cyclotorsional errors. Moreover, we assumed for the study that the torsion always occurred around the intended ablation center. It usually happens that the pupil size and center differ for the treatment compared with that during diagnosis.[21] Then, excluding cyclotorsion, there is already a lateral displacement that mismatches the ablation profile. Further, cyclotorsion occurring around any position other than the ablation center results in additional lateral displacement combined with cyclotorsion.[22] Finally, this analysis considers the results in terms of the residual monochromatic wavefront aberration. However, the visual process is more complex than just an image-projection system and involves elements such as neural compensation and chromatic aberration, which were beyond the scope of this study. The cortical aspect of visual processing especially may affect the subjective symptoms associated with residual wavefront aberration.

With our indirect analysis of cyclotorsional error, we obtained an average error of 4.39°, which, despite the mentioned limitations of the method, agrees with the observations of Ciccio et al.,[23] who reported 4°. The distribution of the percentage of eyes versus cyclotorsional error (Fig. 7) is similar to the findings of Carones,[24] who used a prospective method in a population based on eye registration of recognizable iris structures and reported a mean torsion of 3.3° (range, 0–13°); 224 eyes (74.7%) had less than 4° of cyclotorsion, and 8 eyes (2.7%) had more than 10° of cyclotorsion. In our sample, however, 13% of eyes had cyclotorsion exceeding 10°. These patients would be expected to have at least 35% residual cylinder, 52% residual trefoil, and higher residual errors of tetrafoil, pentafoil, and hexafoil (Table 3). In addition, octafoil would be induced beginning at 7.5° of cyclotorsion.

Because of the cyclic nature, the residual aberration error emanating from cyclotorsional error ranges from 0% to 200% of the original aberration. However, the induced aberrations emanating from lateral displacements always increase with decentration.[25] If we also consider that in human eyes with normal aberrations the weight $C(n,m)$ of the Zernike terms $Z(n,m)$ decreases with increasing Zernike order (n),[18] then the theoretical impact of cyclotorted ablations is smaller than decentered ablations or edge effects[26] (coma and spherical aberration[27]). The results of the work of Guirao et al.[22] and Bará et al.,[28,29] are confirmed by those of the present study, with special emphasis on the independent nature of the cyclotorsional effect with the radial order.

We adopted three criteria based on the accuracy that can be achieved to overcome cyclotorsion: optical benefit provides the maximum angular frequency that can be included in the correction for which an objective improvement in the optical quality can be expected; visual benefit, the maximum angular frequency for which a subjective improvement in the visual

Table 2. Maximum Treatable Magnitude for Different Aberration Components and Different Cyclotorsional Errors for the <0.50 DEQ Criterion

Cyclotorsional Error		Optical Benefit Angular Frequency *m*	Visual Benefit Angular Frequency *m*	Treated Coma $C(n,1)$ (DEQ)	Treated Cylinder $C(n,2)$ (DEQ)	Treated Trefoil $C(n,3)$ (DEQ)	Treated Tetrafoil $C(n,4)$ (DEQ)	Treated Pentafoil $C(n,5)$ (DEQ)	Treated Hexafoil $C(n,6)$ (DEQ)	Treated Octafoil $C(n,8)$ (DEQ)
Torsion tracker	1.5	40	**30**	19.10	**9.55**	6.37	4.78	3.82	3.19	2.13
	2.5	24	**18**	11.46	**5.73**	3.82	2.87	2.30	1.92	1.28
Average torsion	4.0	15	**11**	7.16	**3.58**	2.39	1.80	1.44	1.20	0.81
	5.0	12	**9**	5.73	**2.87**	1.92	1.44	1.16	0.97	0.65
	7.5	8	**6**	3.82	**1.92**	1.28	0.97	0.78	0.65	0.45
	10.0	6	**4**	2.87	**1.44**	0.97	0.73	0.59	0.50	0.35
	12.5	4	**3**	2.30	**1.16**	0.78	0.59	0.48	0.41	0.30
Maximum torsion	14.0	4	**3**	2.05	**1.03**	0.70	0.53	0.44	0.37	0.28
	15.0	4	**3**	1.92	**0.97**	0.65	0.50	0.41	0.35	0.27

In bold: astigmatism, as it is the major aberration mode with a vector nature.

Table 3. Residual Aberration Ratios and Relative Orientations for Different Cyclotorsional Errors

Cyclotorsional Error		Residual Coma $C(n,1)$	Residual Cylinder $C(n,2)$	Residual Trefoil $C(n,3)$	Residual Tetrafoil $C(n,4)$	Residual Pentafoil $C(n,5)$	Residual Hexafoil $C(n,6)$	Residual Octafoil $C(n,8)$
Torsion tracker	1.5	3% @ 271°	**5% @ 136°**	8% @ 91°	10% @ 68°	13% @ 55°	16% @ 46°	24% @ 35°
	2.5	4% @ 271°	**9% @ 136°**	13% @ 91°	17% @ 69°	22% @ 55°	26% @ 46°	39% @ 35°
Average torsion	4.0	7% @ 272°	**14% @ 137°**	21% @ 92°	28% @ 70°	35% @ 56°	42% @ 47°	62% @ 36°
	5.0	9% @ 273°	**17% @ 138°**	26% @ 93°	35% @ 70°	43% @ 57°	52% @ 48°	77% @ 36°
	7.5	13% @ 274°	**26% @ 139°**	39% @ 94°	52% @ 71°	64% @ 58°	77% @ 49°	111% @ 38°
	10.0	17% @ 275°	**35% @ 140°**	52% @ 95°	68% @ 73°	85% @ 59°	100% @ 50°	141% @ 39°
	12.5	22% @ 276°	**43% @ 141°**	64% @ 96°	85% @ 74°	104% @ 60°	122% @ 51°	166% @ 40°
Maximum torsion	14.0	24% @ 277°	**48% @ 142°**	72% @ 97°	94% @ 75°	115% @ 61°	134% @ 52°	178% @ 41°
	15.0	26% @ 278°	**52% @ 143°**	77% @ 98°	100% @ 75°	122% @ 62°	141% @ 53°	185% @ 41°

The percentage is the amount of postoperative residual in magnitude, whereas the angle is the relative orientation of the postoperative residual. In bold: astigmatism, as it is the major aberration mode with a vector nature.

performance can be expected; and absolute benefit, the maximum magnitudes for each Zernike mode for which an effective result can be expected.

When all criteria are met without other sources of aberration, the result is expected to be successful. When only the terms allowed by the visual benefit condition are included, but any of their magnitudes exceed the limits imposed by the <0.50 DEQ condition, the visual performance is expected to improve, but it might not be successful. When terms beyond the limits set by the visual benefit condition are included, the risk that the patient will require time to readapt to the new aberration must be considered. When terms beyond the limits set by the optical benefit condition are included, the risk that the aberrations will worsen must be considered carefully.

Without eye registration technologies,[30,31] considering that maximum cyclotorsion measured from the shift from the upright to the supine position does not exceed ±14°,[23] it is theoretically possible to obtain a visual benefit up to the trefoil angular frequencies and an optical benefit up to the tetrafoil angular frequencies. This explains why classic spherocylindrical corrections in refractive surgery succeed without major cyclotorsional considerations. However, using our limit of absolute residual dioptric error smaller than DEQ 0.50, only up to 2.05 DEQ coma, 1.03 DEQ astigmatism, and 0.70 DEQ trefoil can be corrected successfully. The limited amount of astigmatism, especially that can be corrected effectively for this cyclotorsional error, may explain partly some of the unsuccessful results reported in refractive surgery.

Considering that the average cyclotorsion resulting from the shift from the upright to the supine position is about ±4°,[23] without an aid other than manual orientation, the theoretical limits for achieving a visual benefit extend up to the endecafoil (11-fold) angular frequencies and up to the pentadecafoil (15-fold) angular frequencies for optical benefit. Our limit of absolute residual dioptric error less than 0.50 DEQ increases to 7.16 DEQ for coma, 3.58 DEQ for astigmatism, and 2.39 DEQ for trefoil. The extended limits confirm why spherocylindrical corrections in laser refractive surgery have succeeded.

With currently available eye registration technologies, which provide an accuracy of about ±1.5°, it is theoretically possible to achieve a visual benefit up to the triacontafoil (30-fold) angular frequencies and an optical benefit even beyond these angular frequencies, and using our limit of absolute residual dioptric error less than 0.50 DEQ, up to 19.10 DEQ coma, 9.55 DEQ astigmatism, and 6.37 DEQ trefoil can be corrected successfully. This finding opens a new era in corneal laser refractive surgery, because patients may be treated for a wider range of refractive problems with enhanced success ratios, however, at a higher resolution than technically achievable with currently available systems.[32,33]

To the best of our knowledge, currently available laser platforms for customized corneal refractive surgery include not more than the eighth Zernike order, which theoretically corresponds to a visual benefit range for cyclotorsional tolerance of ±5.7° and an optical benefit range for cyclotorsional tolerance of ±7.5°, which covers most cyclotorsion occurring when shifting from the upright to the supine position. Thus, the aberration status and the visual performance of the patients are expected to improve. Moreover, the same ±7.5° cyclotorsional tolerance means that the magnitudes for the major Zernike modes should not exceed 3.82 DEQ for coma modes, 1.92 DEQ for astigmatic modes, and, 1.28 DEQ for trefoil modes for theoretically successful results.

Based on different criteria, Bueeler et al.[34] also determined conditions and tolerances for cyclotorsional accuracy. Their OT criterion corresponds approximately to our optical benefit condition, and their results for the tolerance limits (29° for 3-mm pupils and 21° for 7-mm pupils) do not differ greatly from the optical benefit result for astigmatism, confirming that astigmatism is the major component to be considered.

In our study, the theoretical percentage of treatments that would achieve an optical benefit was significantly higher than the percentage of treatments that actually obtained a postoperative cylinder lower than before surgery (95% vs. 89%; $P = 0.05$). The percentage of treatments that theoretically would achieve a visual benefit was significantly higher than the percentage of treatments with a stable or improved postoperative

Table 4. Percentage of Treatments That Could Have Been Planned to Achieve an Optical and a Visual Benefit as a Function of the Highest Included Zernike Mode

m	Aberration	Optical Benefit (%) (Residual < Original)	Visual Benefit (%) (Residual < Matching Factor)
1	Coma	97	96
2	**Astigmatism**	**95**	**95**
3	Trefoil	93	92
4	Tetrafoil	92	89
5	Pentafoil	89	87
6	Hexafoil	87	83
7	Heptafoil	84	78
8	Octafoil	82	75
9	Eneafoil	78	74
10	Decafoil	75	71
12	Dodecafoil	71	66
15	Pentadecafoil	66	61
20	Icosafoil	61	58
30	Triacontafoil	57	57
60	Hexacontafoil	55	55

In bold: astigmatism, as it is the major aberration mode with a vector nature.

UCVA compared with the preoperative BSCVA (95% vs. 87%; $P < 0.01$). Both indicate that other sources of aberrations have substantial impact on the final results. The percentage of treatments that theoretically would achieve a visual benefit was higher than the percentage of treatments with a stable or improved BSCVA (95% vs. 91%; $P = 0.09$). That residual cylinder can be corrected with spectacles indicates that other factors induce aberrations and affect the final results. In discussing visual benefit, although VA data are helpful, there may be patients with 20/20 vision who are unhappy with their visual outcomes due to poor mesopic and low-contrast VA, which were not addressed in the present study.

Of interest, the percentage of treatments achieving a theoretical absolute benefit was 93%, whereas the percentage of treatments that actually had postoperative astigmatism reduced to an absolute residual error smaller than 0.50 D was higher (96%; $P = 0.21$).

Finally, the percentage of treatments that theoretically would achieve global success (optical, visual, and absolute benefits simultaneously) was significantly higher than the percentage of treatments that actually obtained a postoperative cylinder lower than the preoperative value, a stable or improved BSCVA, and decreased postoperative astigmatism to an absolute residual error less than 0.50 D (89% vs. 79%; $P < 0.005$). This confirms that cyclotorsion is not the only reason for differences between theory and practice. Wound healing and surgical variation are also keys factors in the outcome.

In summary, the present study showed that cyclotorsional errors result in residual aberrations and that with increasing cyclotorsional error there is a greater potential for inducing aberrations. Thirteen percent of eyes had more than 10° of calculated cyclotorsion, which predicts approximately a 35% residual astigmatic error in these eyes. Because astigmatic error is generally the highest magnitude of vectorial aberration, patients with higher levels of astigmatism are at higher risk of problems due to cyclotorsional error.

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