Laser in situ keratomileusis for mixed astigmatism using a modified formula for bitoric ablation

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PURPOSE. *To evaluate the results of treatment of mixed astigmatism with laser in situ keratomileusis (LASIK) by means of a modified Chayet formula for bitoric ablation and personalized nomogram calculations.*
METHODS. *A retrospective study was conducted in 19 consecutive eyes of 13 patients who underwent LASIK treatment of mixed astigmatism with a mean sphere of +1.63±1.23 D and a mean cylinder of –3.55±1.17 D. The authors used the Schwind ESIRIS Laser platform. The ablation was shifted from the pupil center to the vertex normal of the cornea.*
RESULTS. *Three months postoperatively, the mean sphere was 0.08±0.24 D and the mean astigmatism –0.45±0.31 D. At 3 months, an uncorrected visual acuity (UCVA) of 20/50 or better could be found in 100% of the eyes, and of 20/25 or better in 59%. All eyes were within ±0.5 D spherical equivalent (SE) at 3, 6, and 12 months. No eye lost more than one line of best spectacle-corrected visual acuity (BSCVA). Postoperatively, the corneal wavefront showed a reduction of spherical aberrations and coma, which were analyzed at 4 and 6 mm pupil diameter. The postoperative higher-order aberrations decreased at 4 mm and increased at 6 mm pupil sizes after surgery.*
CONCLUSIONS. *Modified bitoric treatment with the Schwind ESIRIS laser showed an excellent postoperative UCVA and BSCVA with applying external nomogram adjustments. The method demonstrated good predictability, safety, and effectiveness in the treatment of mixed astigmatism. (Eur J Ophthalmol 2008; 18: 869-76)*

KEY WORDS. *Mixed astigmatism, Laser in situ keratomileusis, Schwind ESIRIS laser, modified Chayet formula, Bitoric, Astigmatism*

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INTRODUCTION

Many articles about the treatment of myopia and hyperopia with and without astigmatism by laser in situ keratomileusis (LASIK) have been published; however, there are few dealing with mixed astigmatism (1-11). In the late 1990s, Chayet et al (2, 3) and Vinciguerra et al (12) published toric ablation techniques which apply a myopic and a hyperopic cylinder (90 degrees away).

Although there are different techniques for the treatment of astigmatism with LASIK and photorefractive keratectomy (PRK), cylinder splitting could be demonstrated to be the most tissue saving approach (13).

Chayet et al (2, 3) introduced the bitoric ablation pattern which splits the intended correction into two cylinders, 90 degrees away. The correction of the minus cylinder flattens the steep meridian and the ablation of the plus cylinder steepens the flat meridian, thus achieving a balanced corneal curvature.

As treating a myopic cylinder induces a spherical hyperopic shift (3, 6), the modified Chayet formula (2) (Fig. 1, formula 1 and 2) not only splits the initial subjective refraction into two cylinders of opposite sign, it also accounts for the coupling factor (CF). It is important to de-

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$$(1)\ C_{Myo} = \frac{\left| S_{subj} + C_{subj} \right|}{1.25}$$

$$(2)\ C_{Hyp} = \left| C_{subj} \right| - C_{Myo}$$

Fig. 1 - *Modified Chayet formula of bitoric ablation with a coupling factor of 25%. CMyo = negative cylinder; CHyp = positive cylinder; Ssubj = subjective sphere; Csubj = subjective cylinder.*

$$(3)\ C^{*}_{Myo} = C_{Myo} + \Delta C_{Myo}$$

$$(4)\ C^{*}_{Hyp} = C_{Hyp} + \Delta C_{Hyp}$$

$$(5)\ S_{sett} = C^{*}_{Hyp}$$

$$(6)\ C_{sett} = \left| C^{*}_{Myo} \right| + C^{*}_{Hyp}$$

Fig. 2 - *Steps to calculate the laser setting for the Esiris Hyperopic Astigmatism Menu. CMyo = negative cylinder; CHyp = positive cylinder; _CMyo = offset of the negative cylinder; _CHyp = offset of the positive cylinder; Ssett = laser setting sphere; Csett = laser setting cylinder. Example with the manifest refraction of an eye with +1.5 D sphere and –5.0 D cylinder at 0°: Without coupling, the subjective refraction would be split into a myopic cylinder (CMyo) 3.5 D x 0° and a hyperopic cylinder (CHyp) 1.5 D x 90. Taking into account the coupling factor of 25% by applying the modified Chayet formula* (Fig. 1)*, one has to be aware first to have negative cylinder notation of the subjective refraction. According to formula 1* (Fig. 1)*, one calculates the negative cylinder (CMyo) of 2.8 D x 0° and a positive cylinder (CHyp) of 2.2 D x 90°* (Fig. 1, formula 2)*. The nomogram (Tab. I) was used to alter the theoretical cylindrical components CMyo and CHyp. Thus 0.5 D are added to CMyo resulting in CMyo* of 3.3 D x 0°* (Fig. 2, formula 3) *and additionally 0.75 D are added to CHyp resulting in CHyp* of 2.95 D x 90°* (Fig. 2, formula 4)*. Now in order to insert the correction values into the Hyperopic Astigmatism Menu of ESIRIS software 2.1, the modified cylindrical components have to be recombined into a spherocylindrical refraction* (applying formulae 5 and 6, Fig. 2)*. Therefore the final laser setting is +2.95 –6.25 D x 0°.*

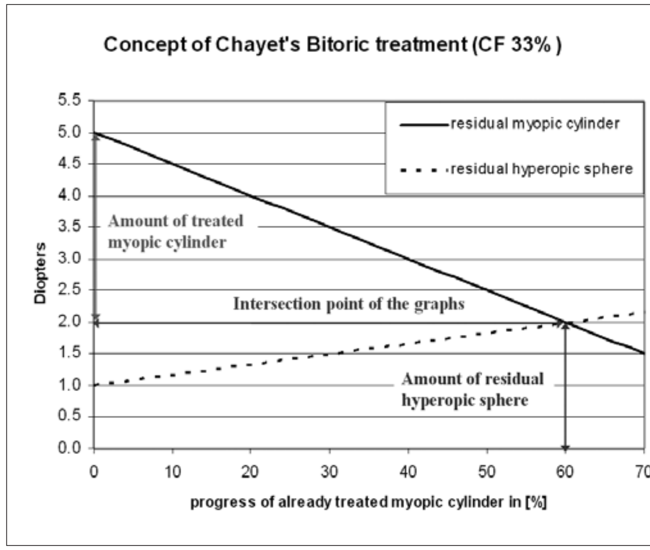

Fig. 3 - *Bitoric treatment and hyperopic shift. Example for +1 –5 D x 180. According to the subjective prescription, the initial spherical error starts at one diopter (dotted line), the astigmatic refractive error begins with 5 diopters (solid graph). Starting with cylindrical correction, each portion of the treated myopic cylinder will reduce the residual myopic astigmatic error. Because 33% of each portion will induce a hyperopic shift onto the sphere, the dotted graph (residual hyperopic sphere) will increase by that amount. During the process of treating the myopic cylinder the idea of Chayet's concept is to reach a condition where the residual myopic cylinder equals the amount of residual hyperopic sphere (intersection of the two graphs). Having treated 3 D of myopic cylinder, one gets equal values at 2 D of residual hyperopic sphere and 2 D of residual myopic cylinder (+2 –2 D x 180). This intermediate prescription will be chanced into positive cylinder notation and hence results in 0 +2 D x 90. Now it is obvious to treat a hyperopic cylinder of 2 D 90 degrees away from the myopic cylinder in order to complete the two-stage treatment.*

note that Chayet found his CF of approximately 33% empirically with his Nidek EC-5000 Excimer laser (3).

In order to use the bitoric approach for individual laser systems and moreover to compensate for systematic over- or undercorrections in different laser systems, the modified Chayet formula (Fig. 1) was extended to obtain final laser settings (Fig. 2, formula 2 to 6).

To clarify the idea of the Bitoric concept we introduced a diagram (Fig. 3) that shows the amount of induced hyperopic shift while treating a myopic cylinder.

The aim of this study was to evaluate the efficacy, predictability, and safety of LASIK for mixed astigmatism performed with the ESIRIS laser system using the modified Chayet formula (Fig. 1) together with adjustments according to a specially developed nomogram (Tab. I).

We demonstrate how to create a nomogram for mixed astigmatism with the data of hyperopic astigmatism and myopic astigmatism. We also show the corneal aberrations that we induce with the bitoric profile ablation.

METHODS

A retrospective study was performed in 19 consecutive eyes of 13 patients who underwent LASIK treatment for mixed astigmatism in the Recklinghausen laser eye center from January 2004 to December 2005. Prior to surgery, all patients underwent a complete ophthalmic examination, including uncorrected visual acuity (UCVA), best spectacle-corrected visual acuity (BSCVA), manifest and cycloplegic refraction, slit lamp biomicroscopy, applanation tonometry, binocularity, corneal topography with the Keratron videokeratoscope (Optikon, Italy), pachymetry, and biometry (Tomey AL 2000, Japan).

Based on topography maps, we also measured the anterior corneal aberrations in terms of root-mean-square values of higher-order aberrations, spherical aberrations, and coma over a 4 and 6 mm pupil diameter.

Exclusion criteria were corneal pachymetry below 500 µm, ophthalmic disease with visual impairment, eyes with previous surgery, and autoimmune diseases.

In all cases we used a personalized customized nomogram.

Postoperative controls were made 1 day and 3 weeks after surgery as well as after 3, 6, and 12 months: a follow-up after at least 3 months was carried out in each patient. Predictability (attempted vs achieved SE within a range of +0.5 D), defocus (SE + half the cylinder value), efficacy (gain/loss of UCVA lines postoperatively versus BSCVA preoperatively), safety (gain/loss of BSCVA lines), and stability were assessed.

Prior to LASIK treatment informed consent was obtained from all patients.

All surgeries were performed by the same surgeon (D.O.), using the ESIRIS laser with software version 2.1 (Schwind Eye-tech-solutions GmbH, Germany). This laser works with a 200 Hz flying/scanning spot, a video eye-tracker with 330 Hz repetition rate, and a 0.8 mm Gaussian-like beam profile.

Lamellar keratotomy with superior hinge was carried out with the Carriazo pendular microkeratome (Schwind Eye-tech-solutions GmbH) in all cases. A new blade was used in each eye.

Preoperatively, each eye received one drop of a topical anesthetic. After positioning the speculum with suction, a second drop of the anesthetic was applied and the cornea was rinsed with balanced salt solution (BSS Alcon Lab). The complete flap was reflected using a spatula. Prior to ablation, the stroma was dried next to the hinge by using a dry sponge. During ablation, the hinge was protected with the sponge and dried again upon visible accumulation of liquid. After flap repositioning, the edges were dried with Merocel sponges. Dexamethasone and ofloxacin eyedrops and lacrimal preservative free eye gel were instilled. The patient received Isopto-Max eyedrops (Alcon Lab.) for 5 days (four times daily) and lacrimal preservative free eyedrops for 6 weeks.

We used ESIRIS version 2.1 to treat mixed astigmatism by means of the hyperopic astigmatism menu. In this menu we get the refraction in a bitoric way; that means the treatment profile is split in a negative cylinder and in a positive cylinder. We obtained the negative cylinder offset values (Tab. I, left column) from analyzing our previous results of myopic astigmatism. The positive cylinder offset values (Tab. I, right column) were derived from previous results of hyperopic astigmatism. We used an average coupling factor (CF) of 25% which was found by multivariate statistical analysis of 100 previous myopic astigma-

TABLE I - PERSONALIZED NOMOGRAM SHOWING THE OFFSET VALUE ADDED FOR EACH CYLINDRICAL COMPONENT

Adjustments for negative cylinder		Adjustments for positive cylinder	
Attempt	**Add**	**Attempt**	**Add**
0.50	0.00	0.50	0.30
0.75	0.00	0.75	0.40
1.00	0.25	1.00	0.50
1.25	0.25	1.25	0.50
1.50	0.25	1.50	0.50
1.75	0.25	1.75	0.75
2.00	0.25	2.00	0.75
2.25	0.25	2.25	0.75
2.50	0.50	2.50	0.75
2.75	0.50	2.75	0.90
3.00	0.50	3.00	1.00
3.25	0.50	3.25	1.00
3.50	0.50	3.50	1.00
3.75	0.50	3.75	1.25
4.00	0.50	4.00	1.25
4.25	0.50	4.25	1.25
4.50	0.50	4.50	1.25
4.75	0.50	4.75	1.25
5.00	0.50	5.00	1.50

tism treatments. The observed coupling factors were not constant for different initial corneal curvatures and varied between 21% and 29% (25% on average). In order to calculate the settings for the ESIRIS laser we used the maximum accepted subjective spherocylindrical correction and the modified bitoric formulae (Fig. 1). An example of our calculations is shown in Figure 2.

To enter the correction into the hyperopic astigmatism menu of ESIRIS software 2.1, the modified cylindrical components have to be recombined into a spherocylindrical refraction using formulae (Fig. 2).

Furthermore, the center of ablation was shifted from the pupil center to the vertex normal of the cornea using the pupillary offset measured with the Keratron videokeratoscope which has been described in a previous report (14, 15).

In all cases an optical zone of 6.25 mm with a transition zone of 0.75 mm was chosen, thus leading to a total ablation diameter of 7.75 mm.

The refractive data were analyzed using the graphs recommend by Waring (16). All data were collected using the software Datagraph-med version 3.20 XP (Pieger GmbH, Germany), and descriptive statistical analysis was performed including vector analysis.

RESULTS

The mean patient age was 40 years (range 21 to 66 years) with 9 eyes of female and 10 eyes of male patients. Nine left and 10 right eyes were treated.

The preoperative refractive mean spherical equivalent (SE) was +0.14±0.95 D (range –1.5 D to +1.63 D), the mean sphere was 1.63±1.23 D (range 0 to +4.0 D), the mean cylinder was –3.55±1.17 D (range –5.25 to –1.25 D).

Refractive outcome

The follow-up at 3 months included 100% of the treated eyes. The mean SE was –0.14±0.23 D (range –0.50 to +0.25 D), the mean sphere was 0.08±0.24 D (range –0.25 to 0.50 D), and the mean cylinder 0.45±0.31 D (range –1.0 D to 0 D).

At 6-month follow-up, 84.2% of the eyes (16 eyes) could be examined. The mean SE was –0.09±0.21 D (from –0.5 to 0.25 D), the mean sphere was 0.13±0.29 D (range –0.25 to 0.75 D), and the mean cylinder was –0.42 ± 0.36 D (range –1.25 to 0.0 D).

At the 1-year follow-up, 84.2% of the eyes (16 eyes) could be examined. The mean SE was –0.12±0.21 D (from –0.50 to 0.25 D), the mean sphere was 0.19±0.38 D (range –0.25 to 1.0), and the mean cylinder was –0.61±0.48 D (range –1.5 to 0.0 D).

Vector analysis was performed with Datagraph-med version 3.20 XP based on double angle scatter plots preoperatively and after 3, 6, and 12 months (Fig. 4).

According to vector analysis the mean cylinder was 2.24 D x 175.8 degrees preoperatively (19 eyes), 0.22 D x 4.2 degrees 3 months postoperative (19 eyes), 0.28 D x 171.5 degrees 6 months postoperative (16 eyes), and 0.44 D x 170.3 degrees 1 year postoperative (16 eyes).

Predictability at 3, 6, and 12 months postoperatively was less than or equal to findings showing an SE within ±0.5 D (SE) in all cases.

After 3 months the postoperative cylinder was minor or equal to –1.0 D in all cases, and –0.5 D or minor in 85% of the cases. Simple regression analysis showed a good correlation between attempted and achieved refraction for sphere and cylinder (Fig. 5).

The defocus equivalent after 3, 6, and 12 months was ±0.5 D in 80% and ±1.0 D in 100% of the cases.

No eye lost more than one line of BSCVA while a gain of two lines could be found in 5% at 3 months and 6% at 6 and 12 months (Fig. 6).

The preoperative UCVA of 20/50 or worse in 95% of the cases compared to a postoperative UCVA of 20/50 or better in 100%, 20/30 or better in 89%, 20/25 or better in 58%, and 20/20 or better in 27% of the eyes at 3 months (Fig. 7).

Comparing the BSCVA preoperatively with the UCVA 3 months postoperatively, there was an efficacy of 90% with a visual acuity of 20/25, 100% with a visual acuity of 20/40.

Concerning stability, the SE was –0.14 (19 eyes) after 3 months, –0.09 D (16 eyes) after 6 months, and –0.12 D (16 eyes) after 1 year.

Corneal aberrometry

By means of the Keratron Scout videokeratoscope, corneal aberrations were measured and analyzed preoperatively and 3 months after surgery at 4 mm and 6 mm pupil diameter. All higher order aberrations presented in this study are expressed according to recommendations of the Optical Society of America (OSA).

The average preoperative spherical aberration was 0.04 µm at 4 mm pupil diameter and 0.24 µm at 6 mm pupil diameter compared to 0.004 µm at 4 mm and 0.04 µm at 6 mm postoperatively.

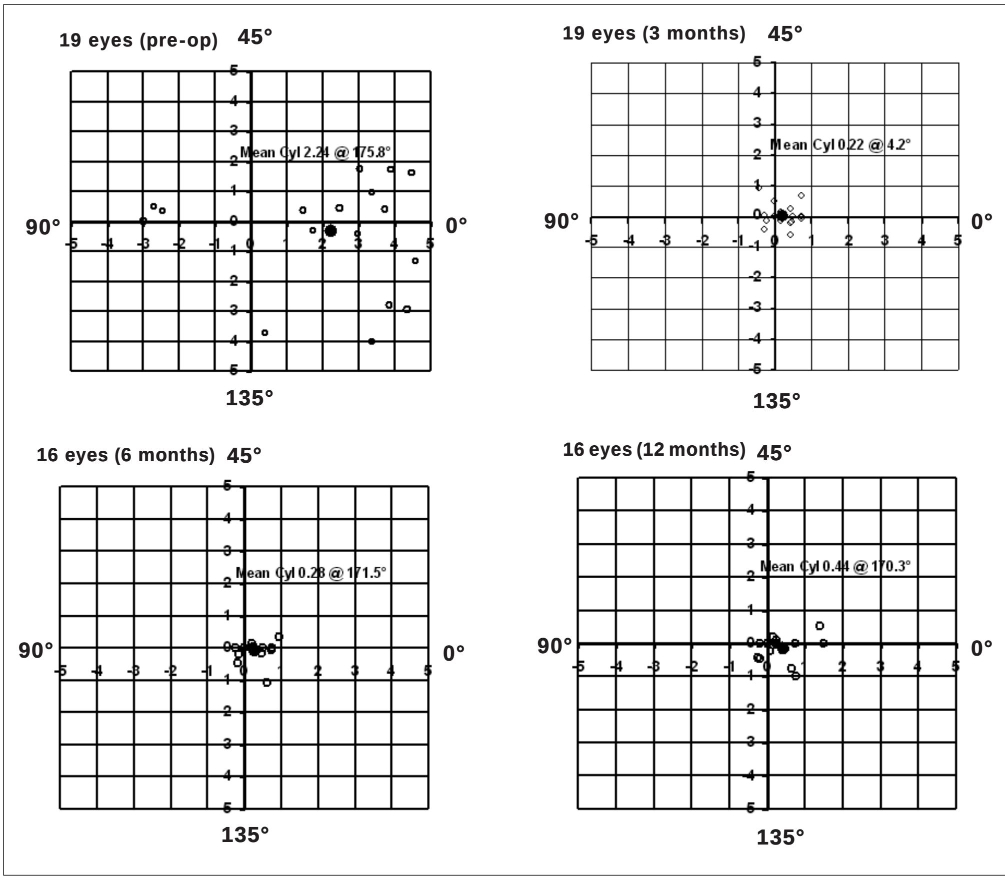

Fig. 4 - *Vectorial analysis preoperatively and at 3, 6, and 12 months postoperatively.*

The coma showed preoperative values of 0.11 µm at 4 mm and of 0.33 µm at 6 mm compared to postoperative findings of 0.08 µm and 0.27 µm, respectively.

The average root mean square (RMS) value of total higher-order aberrations preoperatively was 0.18 µm at 4 mm and 0.52 µm at 6 mm, postoperatively 0.15 µm and 0.57 µm, respectively.

Summarizing post LASIK results, the HOA increased at 6 mm pupil diameter, whereas the HOA decreased over a 4 mm pupil diameter. Coma and spherical aberrations diminished at 4 and 6 mm after surgery.

Corneal asphericity

Preoperative topography measurements with the Keratron videokeratoscope at 6 mm pupil diameter showed a mean asphericity (Q) of –0.18 (range 0 to –0.32), compared to a mean Q of –0.38 (range –0.08 to –0.93) 3 months postoperatively. Thus, there was a negative increase of asphericity with a mean delta Q of –0.20 in our group of patients.

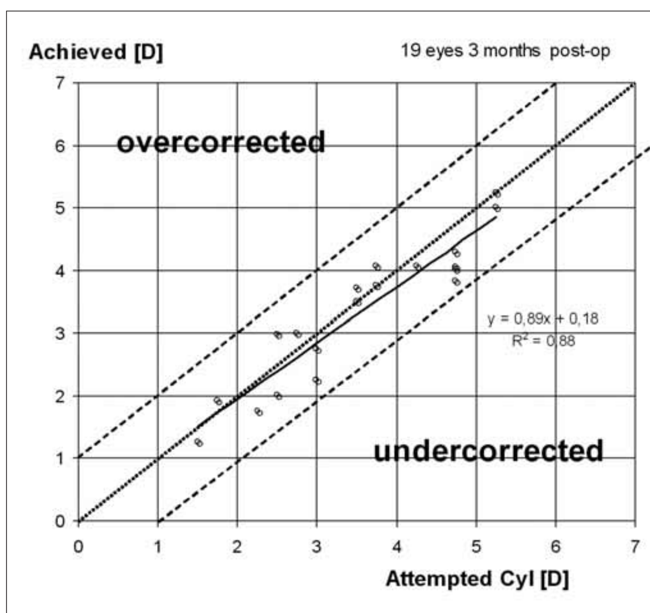

Fig. 5 - *Scattergram of cylindrical values attempted vs achieved 3 months postoperatively.*

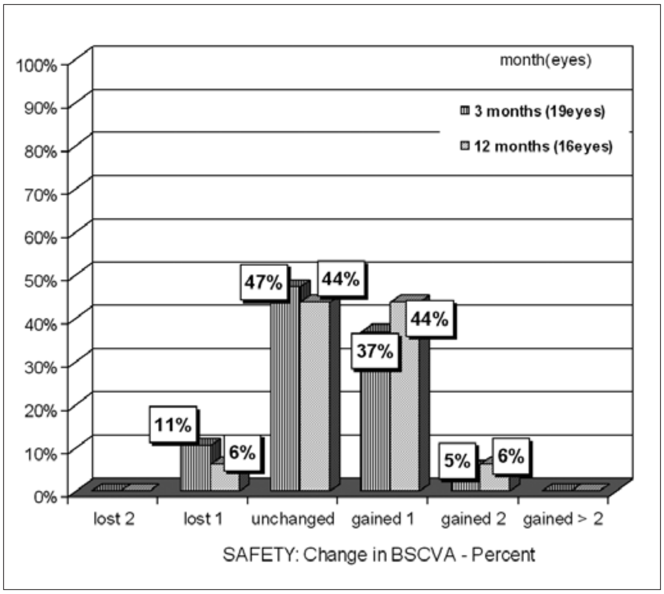

Fig. 6 - *Safety 3 and 12 months after bitoric LASIK-gain or loss of Snellen lines.*

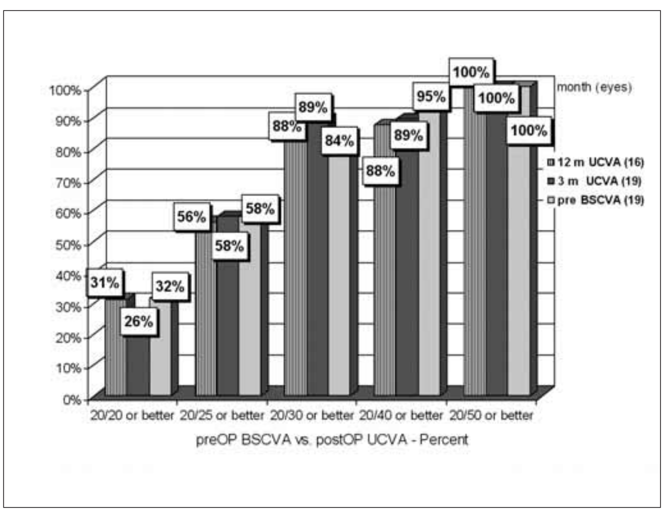

Fig. 7 - *Efficacy in cumulative percentage comparing the preoperative best spectacle-corrected visual acuity (BSCVA) and the postoperative uncorrected visual acuity (UCVA).*

DISCUSSION

The aim of this study was to evaluate the results of treating mixed astigmatism with the ESIRIS excimer laser based on a bitoric ablation profile. The advantage of the bitoric ablation is demonstrated to be the most tissue saving approach (13). In our case we used the ESIRIS excimer laser (SW version 2.1) to treat mixed astigmatism. This software version splits the entered refraction in a bitoric way so we get a myopic cylinder and a hyperopic cylinder 90 degrees away without a coupling factor. In order to compensate for possible over- or undercorrections of the treated myopic and hyperopic cylinders, we found a way to calculate the laser settings for cases of mixed astigmatism (Fig. 2). These calculations are not a trivial task, because one cannot simply add or subtract offset values to the sphere or the cylinder as for compound astigmatism. For this reason we developed a modified Chayet formula which allows to enter offset values (nomogram, Tab. I) for the intended cylindrical components and to use a coupling factor which is different from the one Chayet has discovered with his Nidek laser. To be more specific, the refractive outcome of the bitoric ablation pattern depends greatly on proper data analysis and proper calculation of laser settings. Especially the investigation of the coupling factor remains a rather difficult task, because it seems to be dependent on various factors. Individual excimer laser systems may have different coupling factors, cutting the flap could alter the initial prescription and also different preoperative corneal curvature (K-reading) may have an influence on the coupling factor. For these reasons we performed an unpublished multivariate statistical analysis of 100 previously treated eyes with myopic astigmatism. Subdividing this group into four groups with different defocus, we could derive coupling factors between 21% and 29%. As a first approximation, we applied an average coupling of 25% to the modified Chayet formula. For compensating undercorrections, we adjusted the myopic cylinder and the hyperopic cylinder of the bitoric ablation concept with offset values which we derived from analysis of previous compound astigmatism results (Tab. I).

We recommend that each surgeon should analyze his or her own data and adjust the laser settings accordingly. This will lead to more reliable results.

The ablation center was shifted to the cornea vertex cornea which was measured by means of the Keratron videokeratoscope, as described by us before (14-15). Shifting the ablation center is controversial (17-19). The cornea vertex is in the topography always at the same point; if the patient fixates correctly, it is reproducible and not dependent on the pupil diameter. As we get the measurement in photopic conditions similar to the conditions under the laser with the data of the topography we can shift the ablation center to the cornea vertex, which is why we prefer this point; whether the use of the pupil center is better was not the subject of this study. The centration may have influenced the results as the astigmatism is then treated in a geometric way and this may be a limitation of our study, but as we treat all eyes on the cornea vertex we would not find it ethical to correct a group on the pupil center.

For all eyes we chose an optical zone of 6.25 mm and a transition zone of 0.75 mm, resulting in a total ablation zone of 7.75 mm. Using the standard software, the actual ablation of this laser for an optical zone (OZ) of 6.25 mm is 7.05 mm. This is because the software considers the center of the laser spot as the limit of the 6.25 mm OZ: in this way, the spot having a Gaussian profile of 0.8 mm adds 0.4 mm to each side, thus resulting in an actual OZ diameter of 7.05 mm, leading to a total ablation of 8.05 mm.

The transition zone covered 1.5 mm and seemed to be stable, since no regression could be observed in eyes with a follow-up of 12 months or more. With such a large optical zone in LASIK, a larger transition zone, as given by Carones et al (8), has the disadvantage that the hinge—in our procedure protected by a sponge—is within the calculated ablation area. If the lamellar cut is smaller than the total ablation zone, the cutting edge and surrounding epithelium will be removed, thus making epithelial ingrowth more likely.

Our follow-up included 100% of the cases at 3 months and 84.2% at 6 and 12 months. In none of our cases was retreatment necessary, which is probably due to the appropriate nomogram and good centration. As proof of stability, a longer follow-up and a bigger group of eyes would be more convincing, even though, as displayed in the study of Rashad (20), the refractive spherical and astigmatic results are stable after 3 months.

In our group of patients we had a decrease in corneal aberrations measured by the topographic system at 4 mm, and at 6 mm the HOA showed a slight increase; however, a decrease in spherical aberrations and coma could be observed at 4 as well as 6 mm in the 3-month follow-up examination. Llorente et al (21) measured the corneal aberration induced in hyperopic LASIK and found a significant increase in HOA. They also found an inducement of negative spherical aberrations in hyperopes and a positive inducement in myopes. Similar results were reported by Wang and Koch (22) and Albarrán-Diego et al (23).

An explanation why the spherical aberrations did not increase in our study might be that in mixed astigmatism one meridian is treated in a myopic way and the other meridian in a hyperopic way, so that the SE was near 0 D in our patient group and inducement was low for the global treatment. The centration of the ablation might play a role, since a coma decrease could be observed in our group of patients after LASIK. A comparative study is required to confirm these results.

Similar to the measurement in hyperopic LASIK (24), we found an increase in asphericity towards a more negative value, which will provide the patient with more depth of focus.

Our data allow the conclusion that bitoric LASIK using the ESIRIS laser system, with a laser setting of a 6.25 mm optical zone and a 0.75 mm transition zone, is a predictable, effective, and safe method in the treatment of mixed astigmatism with a cylinder up to –5.25 D. Furthermore, Chayet's formula and our modifications are also applicable for pure myopic astigmatism. We successfully treated two eyes that we did not include in this study in order not to mix study groups.

No propertary interest. Dr. Diego de Ortueta is Consultant for Schwind eye-tech solutions (Kleinhostheim, Germany).

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